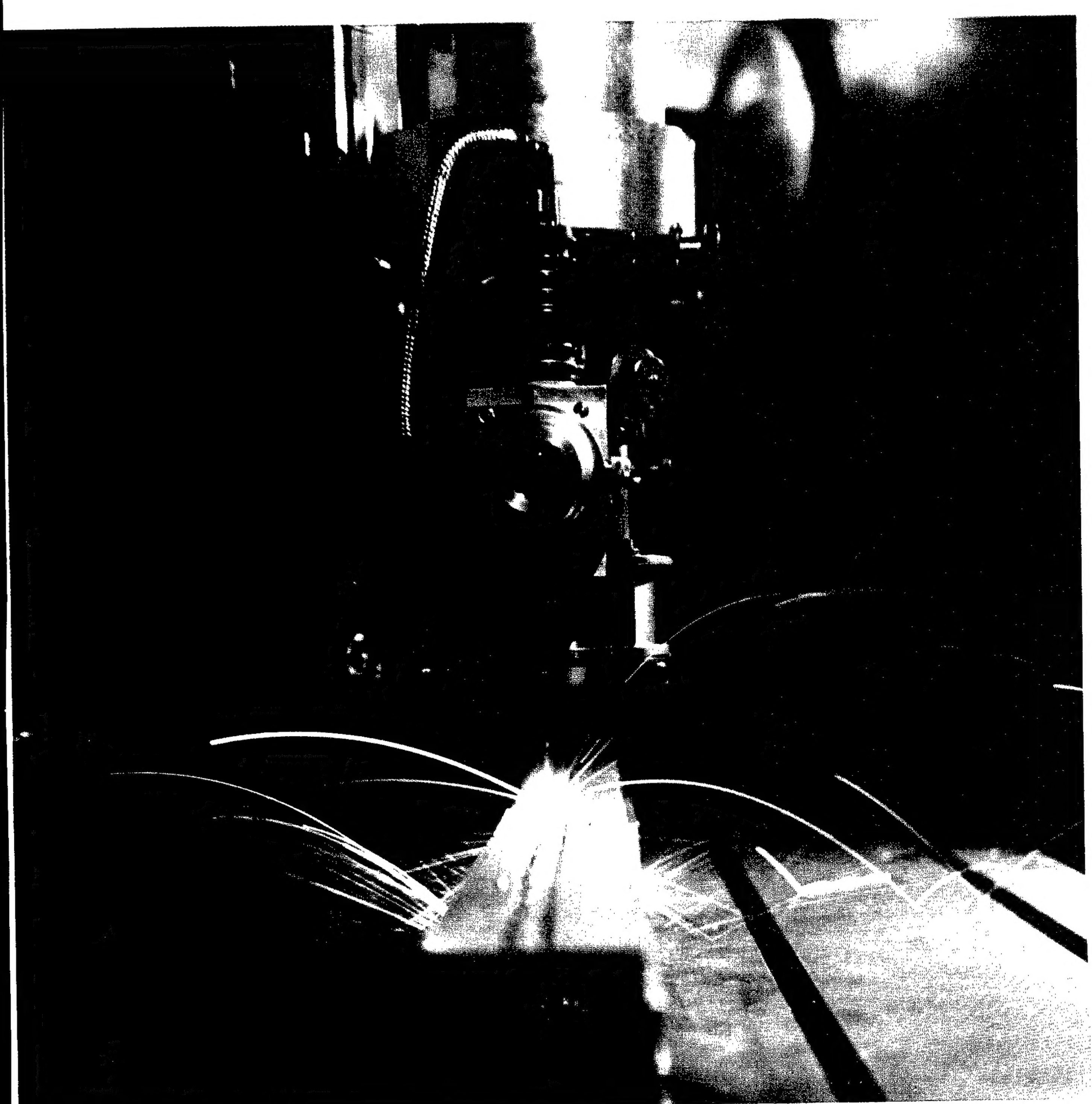
US Army

ManTech Journal

Joining Leaps Ahead

Volume 4/Number 1/1979



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US Army ManTech Journal

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ABOUT THE COVER

An electron beam weld is shown being made in a one inch thick titanium plate to certify welding parameters at Grumman Aerospace Corporation in Bethpage, New York. The entire gun shown is enclosed in a 12 x 12 x 35 foot vacuum chamber at 10-4 torr.

Comments by the Editor

DR. JOHN J. BURKE

One of the areas of greatest accomplishment in the Army's wide range of manufacturing technology projects has been that of joining, not only in regard to armor as one would expect, but also relative to basic technologies such as diffusion bonding, electron beam welding, and laser welding. In this issue of the Army ManTech Journal, we feature these topics; and we also are most happy to give readers an article describing one of the remarkable achievements that our sister service, the U. S. Navy, has attained—specifically, superplastic forming/diffusion bonding.

The article on the U. S. Army Tank-Automotive Research and Development Command's programs lists topics covering every facet of new joining technology, and it is most interesting to note that TARADCOM's plans to establish and implement an integrated system of research and development of new joining technology includes a thrust toward consistency with the Air Force's ICAM Program. The full result sharing concept of this program reflects the universal attitude of cooperation among the military services and industry and must be commended.

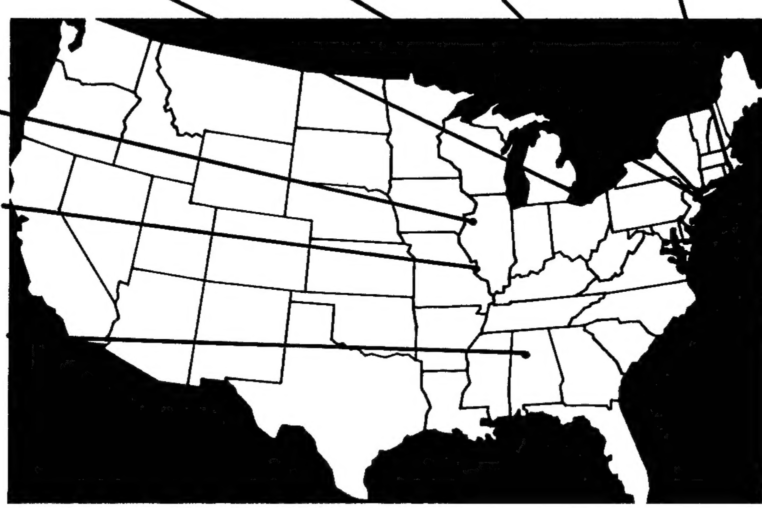
The article on welding nonferrous rotating bands on artillery projectiles represents a milestone in the implementation of a viable automated arc welding system. This development serves as a model for private entrepreneurs who have the vision to commercialize the developments from R&D funded by the Army. This will serve to further benefit the Army's production base capability, which is the prime overall objective of these Army sponsored programs.

Fantastic returns from the programs on electron beam welding and laser welding also are highlights of this issue, with the former providing drastic reductions in labor and energy costs and the latter dramatically slashing the costs of welding a most complex piece of equipment. Both technologies produce bonds with extremely localized fusion, a characteristic that makes possible the joining of materials and components never before feasible in a production mode. Truly a product of revolutionary technical developments in the field of joining.

The article on new torsion bars for the Army's Armored Personnel Carrier and Infantry Fighting Vehicle tells a story about what sometimes occurs during the course of a research and development program. In this case, a marked price increase in the prime material of interest forced researchers to look in an entirely different direction for the solution to their challenge. Such a set of circumstances may beset scientists more and more frequently as the costs of materials for military use continues to spiral.

This issue of the ManTech Journal also marks the beginning of another year of publication, a year which will feature a special, comprehensive treatment of electronics in the Army and the outstanding accomplishments of Army researchers in the area of new electronics manufacturing technology. Also planned for this year of publication are numerous articles on CAD/CAM and Group Technology, along with a wide variety of technical reports on every topic within the scope of the Army production base. The coming issue on the electronics commands will be the most comprehensive coverage to date of these varied organizations and it should serve to clarify for many manufacturing people outside the Army how the new division of responsibilities is assigned and carried out. This reorganization has been several years being implemented, and now that it is complete, this next issue of the ManTech Journal will be most timely with its series of articles on the activities of these newly formed organizations.

DARCOM Commands Actively Implementing New Manufacturing Technology Methods



TARADCOM's Goal: Automated Welding System

SAM GOODMAN is a Materials Engineer with the U. S. Army Tank Automotive Research and Development Command, where he serves as the prime point of contact for TARADCOM's manufacturing technology programs and also is Project Engineer on several specific programs. Prior to rejoining TARADCOM three years ago, Mr. Goodman worked for about twenty years as a welding engineer for General Dynamics' Boat Division, Westinghouse Corp., and Bechtel Corp., where he was involved with welding problems on nuclear reactors. He worked for seven years earlier at TARADCOM after receiving his B.S. in Metallurgy from Wayne University in 1950. He has been directly involved with laser welding of armor and recuperators and with laser heat treating, and he also has gained considerable experience with flexible machining systems. A Registered Professional Manufacturing Engineer in the State of California, Mr. Goodman is an active member of AWS, ASM, ASME, and ASNT.

Photograph

Unavailable

JAMES L. CHEVALIER is a Materials Engineer with the U. S. Army Tank Automotive Research and Development Command, where he serves as Team Leader of the Metals and Joining Function. Prior to joining TARADCOM in 1979 as Team Leader, Dr. Chevalier worked for seven years at the U. S. Army Aviation Research and Development Command on the HLH helicopter and the 214A aircraft projects. He earlier had worked at NASA-Lewis on research programs for bearings, gears, and the materials used in their fabrication. From 1969 to 1970 he was with the U. S. Naval Air Systems Command in Washington, working on corrosion problems and nondestructive testing. He received his Ph.D. in Metallurgy from Case Institute in 1969, later obtaining his LL.D. from St. Louis University in 1975. He is a member of the bar in Missouri and Michigan and retains memberships in ASM, ASME, ASLE, and Sigma Chi.

State of the Art Prototype

Automation in the welding of armor vehicles—therein lies the key to lowering their costs of fabrication and to compressing the time required for rapid mobilization. The U. S. Army Tank Research and Development Command (TARADCOM) is heavily engaged in a new program that is intended to unravel many of the riddles in the puzzle. Riddles on how best to bring forth a truly effective automated system of welding.

But the road to success in this venture still contains many pitfalls and obstacles that are yet to be surmounted before the nation's arsenal will possess this full capability. Many are the unanswered questions that still must be resolved by this program before our armor vehicle industry can safely say it "can do" on short notice.

Program Variety Continues

Joining programs at TARADCOM continue to cover a variety of processes and materials, with the primary concern being that of welding armor vehicles. This emphasis stems from the substantial amount of welding involved and its highly labor intensive character. Welding has been identified as the second most costly process (after machining) employed in armored vehicle fabrication. The escalating cost of labor and a diminishing supply of qualified welders makes the solution of this problem one of critical dimensions. It therefore is viewed as a primary area for Manufacturing Methods and Technology programming.

Many current programs address the problems as did past programs by attempting to adapt newer welding processes offering higher deposition rates to armor fabrication. Among such programs are

- Gas Metal Arc Welding (GMAW) of Armor (Steel)
- Electron Beam Welding of Armor (Aluminum)
- Submerged Arc Welding With Powder Metal Additions (Steel)
- High Deposition Welding (GMAW) of Armor
- Heavy Aluminum Plate Fabrication
- Laser Welding of Armor
- Joining of Dissimilar Metals
- Automated Welding of Hull Structures.

Integrated Automation Approach Initiated

The last program listed above represents an attempt to provide "automation". The effort proved unsuccessful and work has been terminated pending reevaluation. The quotation marks around automation are intended to convey the fact that many so-called automation efforts in welding in reality represent only mechanization.

As can be seen, the programs are diverse and attack a single problem (armor welding) from a variety of directions. We recently reexamined this method and concluded that our lack of success in achieving the automation has been because our approach is fragmented. We have not been employing the diverse technologies and technical capabilities which can help solve the problem.

To achieve a breakthrough in automation, a coordinated program is being undertaken to integrate existing expertise and technology and then to address a selected application such as the XM-1 or XM-2 hull. The approach is, through systems integration, involving expertise in welding process control; sensory technology (including various developed sensors of temperature, pressure, electro-optical events, etc.); stress analysis related to thermal stresses; computer control; and other technologies that are identified as relevant and available.

Test Bed for Newer Technology

The project is developing a prototype system incorporating state-of-the-art technology. Reports and software will be provided to disseminate the technology, and requirements for new developments will be identified. The prototype system is being

assembled, operated, and evaluated in an off-line location at a selected fabrication facility. When proven, it will be duplicated or replaced so that it may continue to be used as a test bed for newer technology emerging from current and planned R&D.

A program of two phases and multiple tasks is under way. Phase I of the program will be a work definition effort to identify materials, processes, participants, and technology to be exploited and to acquire the basic hardware to be employed. A first cut computer program incorporating known relationships of process parameters and associated physical/mechanical events is being established, and necessary studies are being defined to verify and/or improve it.

Phase II will provide iterative programs to incorporate in an automated system the results of selected tasks such as

- Arc welding sensor application
- Weld geometry prediction
- Adaptive control welding skate
- Electro-optical weld observation
- Thermal stress during welding
- Out of position welding
- Improved weld power supplies.

Known Materials, Procedures Addressed

No single technology can address all these requirements, so an ongoing effort by experts from a variety of disciplines must be maintained. The program will also maintain awareness and will feed from ongoing R&D efforts, translating that research into a useful tool to accomplish automatic welding.

It is anticipated that by the conclusion of Phase II a prototype system usable in production will have been achieved and implemented in a vehicle fabrication plant. Follow-on phases would provide refinements for the initial prototype and extend its capability to additional products and welding processes.

At this time we envision the welding program as addressing materials and procedures known to be usable. The question of material weldability should in all probability be addressed as a separate task or program. In other words, the prototype automated system will be based initially on the assumption that the material introduced has been tested or examined in such a way as to verify its weldability by the process(es) to be used.

Full Result Sharing Planned

Also within the integration concept is an effort to establish an automated work cell consistent with the Air Force's ICAM Program for an Integrated Computer Aided Manufacturing Plant.

Implicit in this program will be a requirement to interact with the research community, existing technical organizations such as AWS and WRC, other users and suppliers of welding technology, and the other military services to make certain that the results are shared and usable by as large a segment of industry as is possible. Relative to the R&D community, this sharing will involve the identification of problems requiring research and development and the early adaptation of R&D results to the pilot capability.

DONALD E. PHELPS is a Senior Project Engineer at the U.S. Army Tank Automotive Research and Development Command (TARADCOM). He holds a B.S. in Chemical Engineering from Tri State College, Angola, Indiana. Mr. Phelps has been associated with various activities related to armor and its fabrication since 1952. He currently is a Materials Engineer in the Armor Application Function of the Combat Systems Division, Tank Automotive Systems Laboratory, TARADCOM.

ROBERT MESSLER, JR., is Group Head of the Advanced Metallic Structures Group of the M&M Development Section at Grumman Aerospace. His experience encompasses metallurgy, welding, forming, and nondestructive testing in areas ranging from advanced development to production and manufacturing support. He has served as project engineer on programs pertaining to electron beam (EB) welding thermal analysis, weld defect prevention and repair, NDT defect correlation in builtup structures, diffusion bonding, metallurgical and tooling development aspects of the SPF and SPF/DB programs, plasma arc welding (PAW) repair of advanced titanium alloys, friction and wear damage and protection, boron/aluminum comnd aluminum alloys. He holds a B.S. in Metallurgical Engineering from Rensselaer Polytechnic Institute (1965) and a Ph.D. in Physical Metallurgy from Rensselaer Polytechnic Institute (1970).

EB Welding of Armor

Lower Weld Time, Costs

Welding of armored vehicle hulls is a costly, time consuming operation, so potential savings through process improvements can be significant. Electron beam welding is one alternative process that can slash the production costs now incurred using multipass gas metal arc (GMA) welding.

In a program for the Tank Automotive Research and Development Command (TARADCOM), Grumman Aerospace Corporation welded a nearly full size aluminum hull using the electron beam process. The approach Grumman took allowed them to develop and demonstrate production concepts and procedures, as well as weld parameters. Their work has shown that electron beam welding can

- Reduce weld time by 75 percent
- Reduce the number of operators by 67 percent
- Reduce energy consumption by 80 percent
- Eliminate the use of welding concumables (shielding gas and filler metals).

All of which adds up to very considerable cost savings. Two additional, but less tangible benefits, would be improved weld quality, which would reduce repair time, and the ability to automate the process. Furthermore, tooling and joint preparation costs would be virtually the same as for GMA welding.

A possible drawback to electron beam welding is the steep initial equipment cost when compared to GMA welding. However, if these costs are amortized over the typical number of production units, the projected savings remain very significant.

Part of Larger Effort

The work at Grumman is part of TARADCOM's Manufacturing Technology Program, which involves working with industry to establish and implement the latest, most advanced fabrication techniques and processes. This program is in line with TARADCOM's larger objective to shorten production lead times and lower production costs of armored vehicles.

Aluminum armored vehicles are now fabricated by a combination of manual, semiautomatic, and automatic GMA welding. The GMA process uses an inert shielding gas, usually argon, and an aluminum alloy filler metal. The thick joints of typical armored vehicles (1¼ to 1¾ inches) require multiple weld passes (usually three to five). And the main joints require welding from inside as well as outside the vehicle. The inside welds must be made manually because of limitations on maneuverability of the automatic equipment. Thus, weld quality depends on the individual welder's ability and may vary widely. Extensive rework often runs the field cost up to many times that of the original weldment.

On the other hand, all electron beam welds on the prototype hull were made in a single pass. Out of twenty-three welds, only one repair was required—that was due to a beam oscillation malfunction. Radiographic and ultrasonic inspection of these welds showed no missed seams, cracks, or lack of penetration. Although there was some porosity in most welds, it was within established acceptance limits. Weld shrinkage and distortion were minimal.

EB Welding Characteristics

Why the reduced welding time and superior welds? Very briefly, electron beam welding concentrates a beam of electrons to produce melting and joining in very localized areas. The dense stream of high velocity electrons is emitted, focused, and accelerated by an electron beam gun (shown in Figure 1) consisting of a cathode and an anode. The required heat is produced by conversion of the kinetic energy of the electrons. Welding is done in a vacuum to protect the electron emitter (cathode) in the gun and to eliminate atmospheric interference with electron travel.

Electron beam welding produces extremely narrow welds with deep penetration, in contrast to the broader multipass fusion pattern of conventional arc and gas welds, as shown in Figure 2. Thus, single pass, low distortion welds can be made from one side at high speed (up to 100 inches or more per minute).

This is all made possible by the mechanism of heating with electron beam welding. With conventional arc and gas welding sources, melting occurs at the surface of the workpiece. Penetration comes about largely through conduction of heat in all directions from the heating source. With an electron beam, the energy density is so intense that it almost instantly vaporizes a hole through the entire joint thickness. The walls of this hole are molten, and as the beam moves along the joint, more metal is melted on the advancing side of the hole. The molten metal flows around the periphery of the hole and solidifies to the rear to make a weld. If desired, a less intense beam will produce a partially penetrated weld of the same narrow configuration.

The combination of high speed, single pass welding and the vacuum environment results in significant reductions in both welding and repair time. And electronic beam welding is easily and efficiently automated. The movements of the electron gun, welding power, welding speed, and welding sequence can all be automated and programmed, allowing reproducible welds. Automation not only reduces handling and welding time, but ensures uniform weld quality.

Work Began In 1972

The Army became interested in the possibility of incorporating these advantages into hull fabrication several years ago. Welding of the prototype hull at Grumman followed initial process feasibility studies at the U.S. Army Tank Automotive Command in 1972, and development of welding procedures at Grumman starting in 1974.

A particularly important development in the early Grumann work was that of wide beam welding by electromagnetic beam oscillation. This technique made low cost joint preparation (by saw cutting, for example) possible.

Based on the success of these earlier programs, a contract was initiated with Grumman in September 1976 to design, develop, and fabricate tooling for a prototype hull and to demonstrate the operation of this tooling and the electron beam welding system by fabricating one hull.

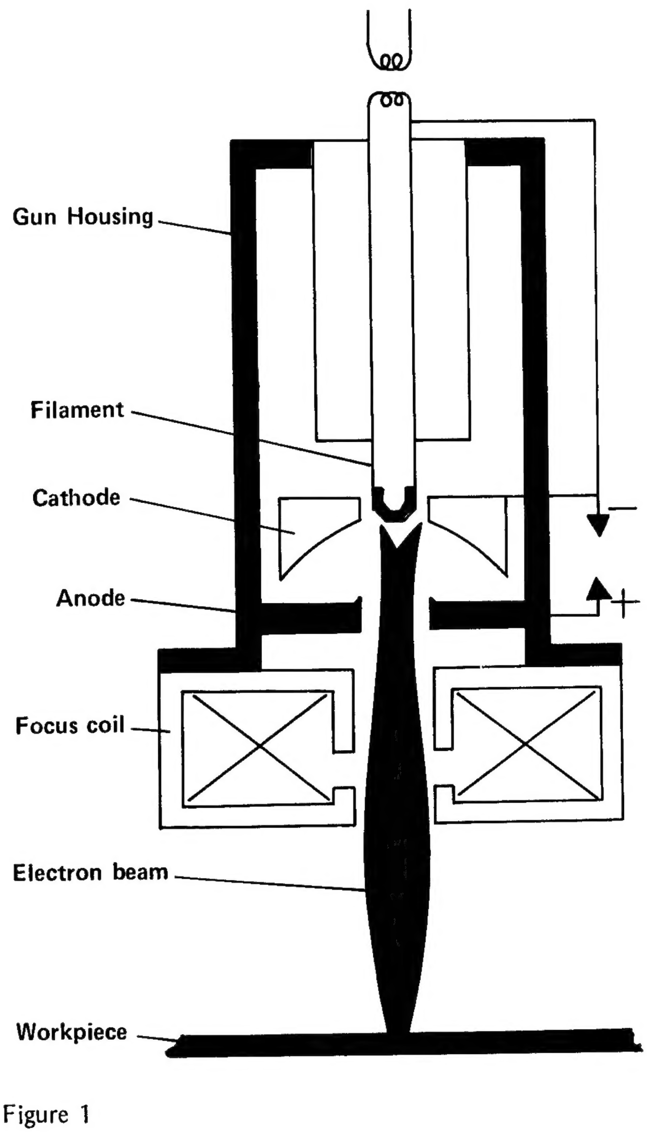


Figure 1

M113A1 Serves As Prototype Model

The M113A1 armored personnel carrier was selected for the prototype work. This vehicle represented a large class of aluminum (5083 alloy) armored vehicles currently in service but also typified proposed future vehicles.

All external hull weld joints on the M113A1 were redesigned for electron beam welding. The design, shown in Figure 3, consisted of a combination of scarf butt and corner splice joints. The vehicle upper and lower side panels were machined to produce a 0.200 inch deep step around the panel perimeters. The vehicle top, bottom, sponson seat plates, and upper and lower forward and aft bulkheads were saw cut to width. The transverse mating scarf joints were profiled with a ship shaper miller. These parts were then sandwiched between the side panels and electron beam welded.

This design minimized joint preparation costs and simplified tooling by self alignment of the components. To improve performance against ballistic impact, the number of welds that would be "visible" to projectiles was minimized and the welds were designed so that high probability impacts would load the joints in compression rather than shear. All joints were designed for single pass welding from the outside.

Modular Approach To Assembly

Grumman adopted a modular approach to vehicle assembly (shown in Figure 4) in which subassemblies were fabricated by welding of details. The subassemblies were then welded together to form a complete hull. Three subassemblies were employed:

- The upper module, including the vehicle top, upper side panels, and the upper forward and aft bulkheads. This assembly required eight welds.
- The sponson angles, including the lower side panels and the seat plates. This assembly required two welds.
- The lower module, including the sponson angles and the vehicle bottom, which required two welds.

The final assembly involved joining the upper and lower modules and adding the lower forward and aft bulkheads. This required eleven welds. The hull is assembled upside down for better accessibility during welding. Figure 5 shows the prototype hull during various stages of fabrication.

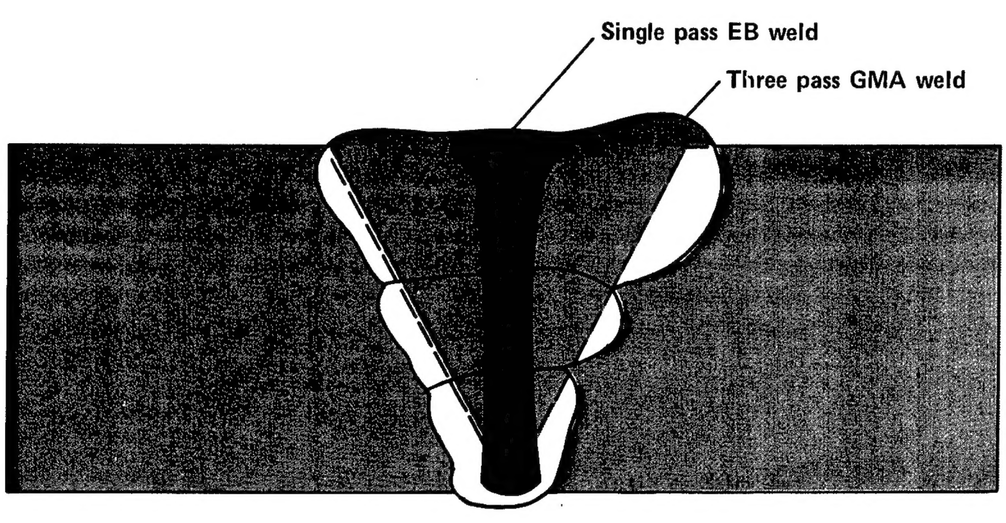


Figure 2

Manufacturing Procedure

The modular approach simplified joint design, fixturing, and assembly. It also permitted production concepts and procedures to be developed and demonstrated. The production manufacturing plan recommended as a result of this work employs three chambers and four electron beam guns and powr supplies. It uses tooling that can produce multiple assemblies in a single chamber pumpdown. The plan requires that the detail parts be manufactured so that they are dimensionally reproducible and interchangeable from hull to hull. Only the electron beam gun movement and power settings for welding the forward and aft bulkheads are automated, but automation can be used in other areas as well. The production rate with this facility would be twelve hulls per two 8-hour shifts.

The proposed production tooling is designed to reduce the time required for setting up the details in the fixture besides improving throughput by permitting multiple subassemblies to be loaded and welded in a single pumpdown. Most welds are performed in the downhand (i.e., gun overhead) position and in the x-axis. Within a subassembly, the gun automatically indexes to the next joint location as each weld is completed. On multiple setups, successive subassemblies are automatically rotated into position for welding. Two independent guns are employed on the final assembly so that the bulkheads at each end of the hull are welded simultaneously.

Dividends of EB Welding

Table 1 compares the number of passes, typical welding speeds, welding times, initial equipment cost, consumables, and relative energy costs for electron beam and GMA welding of the hull. Electron beam welding is shown to offer marked reductions in labor, consumables, and energy use. These differences are quite significant if one considers the amortization of the high initial equipment cost over the typical number of production units.

As noted before, weld quality was improved in the prototype electron beam welds. Only one repair weld was requiredout of twenty-three welds; weld shrinkage averaged less than 0.015 inch per joint; and distortion never exceeded 0.250 inch on any component or subassembly. As a result of this program, electron beam welding is seen as a very promising alternative in the fabrication of aluminum armored vehicle hulls.

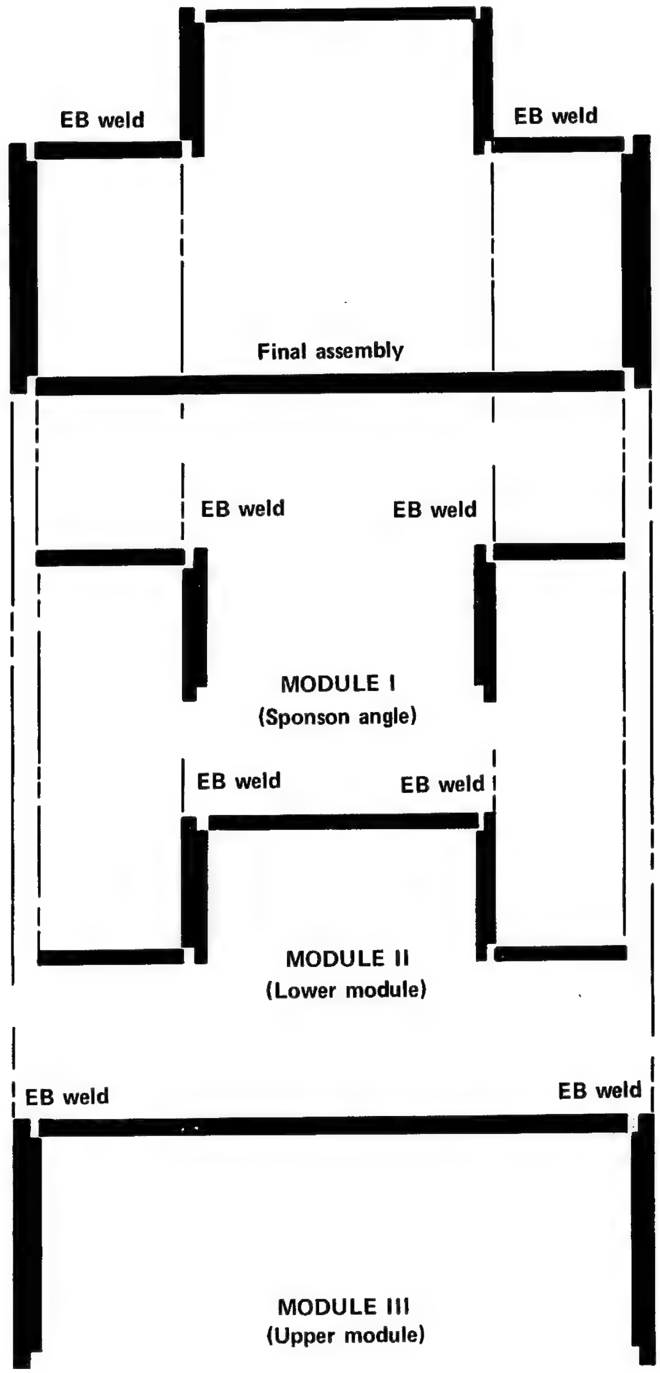
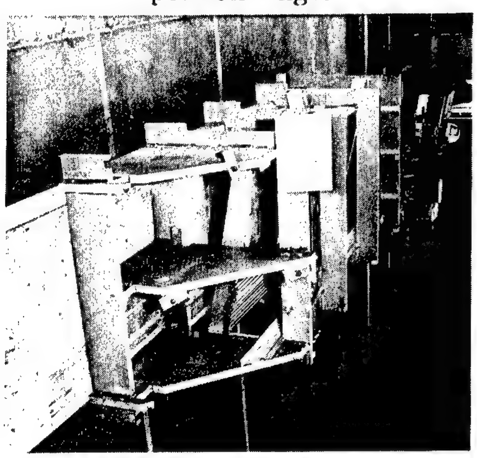


Figure 3

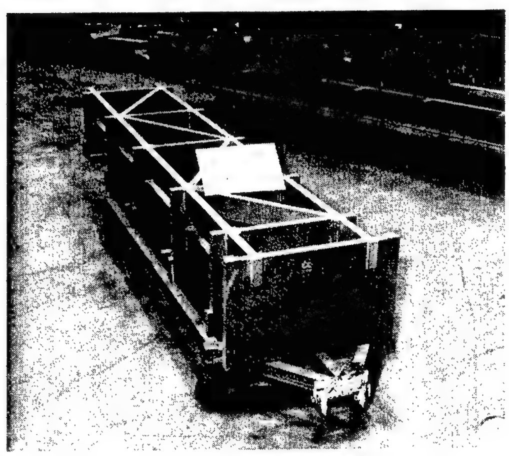
ITEM	EBW	GMAW
NUMBER OF PASSES PER JOINT	1	5
WELDING SPEED (INCHES PER MINUTE)	18	16 – 20
TOTAL LENGTH OF WELD PER HULL (INCHES)	1882	9410
TIME TO WELD PER HULL (MINUTES)	123.9	525
LINEAR HEAT INPUT (KJ PER INCH)	43	38.8
WELDING ENERGY CONSUMPTION PER HULL (KW PER HR)	22.4	101.4
CONSUMABLES (PER HULL)		
SHIELDING GAS (CU FT)		525 (ARGON)
FILLER METAL (LBS)		188 (5356)
INITIAL EQUIPMENT COST	$4,800,000	$100,000
NUMBER OF WELDERS/OPERATORS	8	24

Table 1

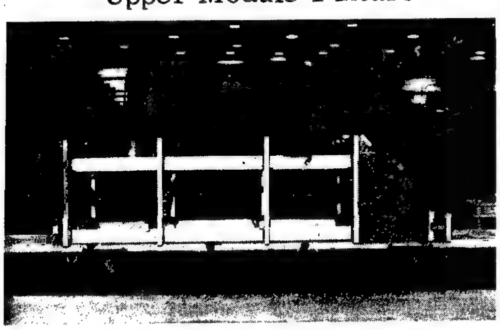
Sponson Angle



Lower Module



Upper Module Fixture



Lower Module Fixture

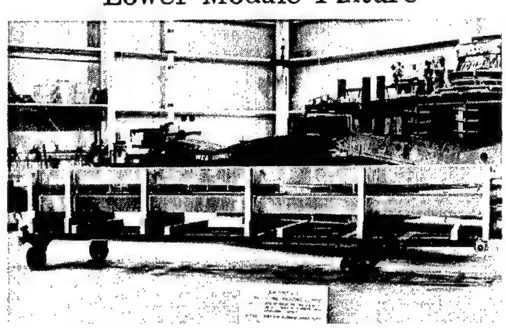
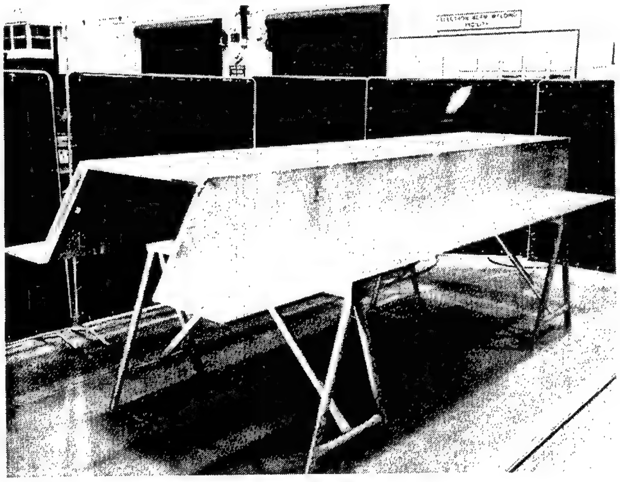
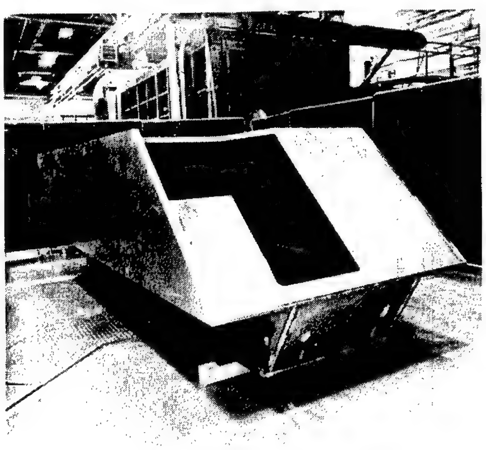


Figure 4

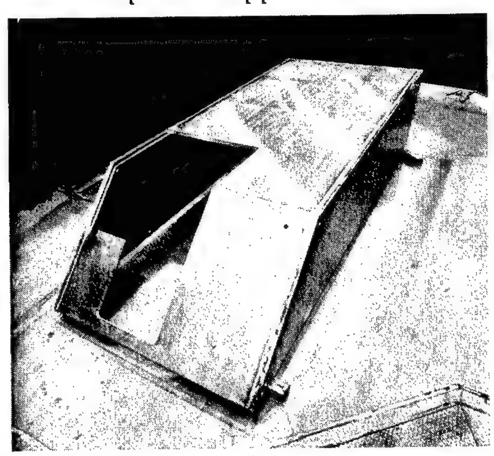
Completed Lower Module



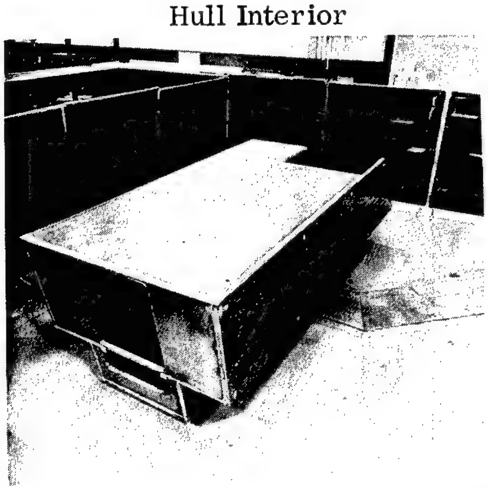
Forward



Completed Upper Module



Hull Interior



Aft

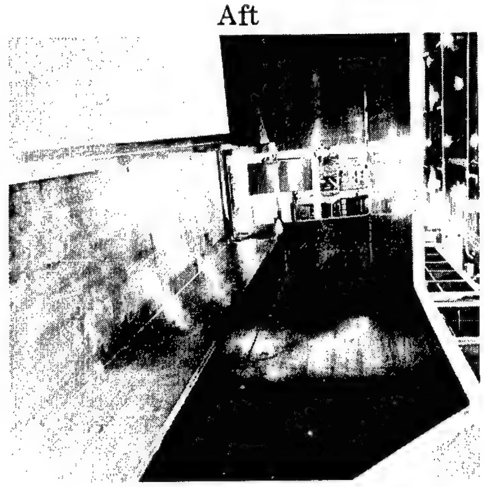
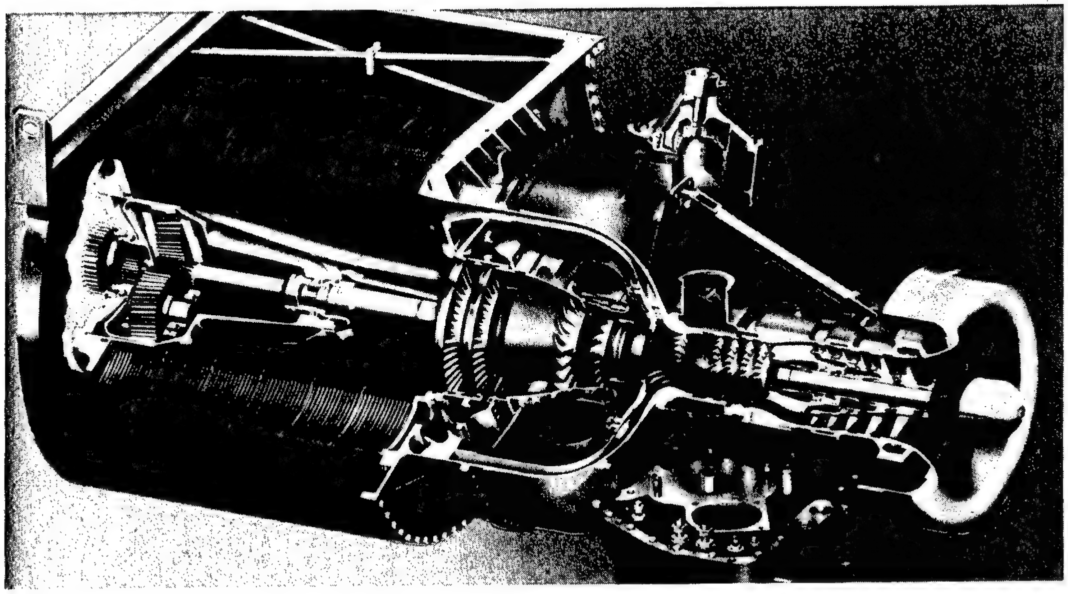


Figure 5

Complex Task Less Complex

Laser Welding Cuts Costs 63%



Imagine a highly complex assembly requiring over 10,000 feet of welds involving over 5000 separate passes—that's the challenge that design engineers faced when setting up production of the recuperator heat exchanger for Avco Lyoming's AGT 1500 gas turbine. The engine is the power plant for the U. S. Army's XM-1 tank (Figure 1).

Computer controlled laser welding machines were the solution turned to by Avco's manufacturing engineers as having the greatest potential for reducing this enormous welding task to an efficient, economical procedure replacing the currently used resistance seam welding technique.

The AGT 1500 recuperator is a thin plate heat exchanger made by welding together 580 plates of 0.008 inch thick Inconel 625, each having 20 air passage holes of complex shape that have to be welded to seal off gases and air passing through the recuperator (Figure 2).

Resistance Welding Used First

The fabrication of a recuperator core basically involves preparation of details, joining the details, and pressure testing. During the early development phases of recuperator core design and fabrication, various joining processes were considered—several brazing techniques and inert gas-tungsten arc, plasma arc, and electron beam welding.

The results of tests using subsized specimens showed problems with each of these, such as complex set-ups and slow travel speeds. Resistance seam welding eliminated the requirement of precision alignment and offered a reliable joining method. The problem with accessibility for ID and OD welding in the tight space between the plates (about 0.065 inch) was solved by developing a special welding head (Figure 3). Resistance seam welding is currently used to join the two kinds of convoluted plates. Though satisfactory, the standard 60 cycle seam welding procedure is limited to a maximum travel speed of about 50 inches per minute.

JULE A. MILLER joined Avco Lycoming in 1963 and in 1978 was promoted to General Supervisor, Joining Technology. In this position he has technical responsiblilty for all welding and brazing, with both the Joining Development and Production Support Groups reporting to him. Prior to joining Lycoming, he was employed by the Sikorsky Aircraft Division of United Technologies Corporation. He is an alumnus of Nasson College and the University of Michigan and is a member of the American Welding Society's Committee on Brazing.

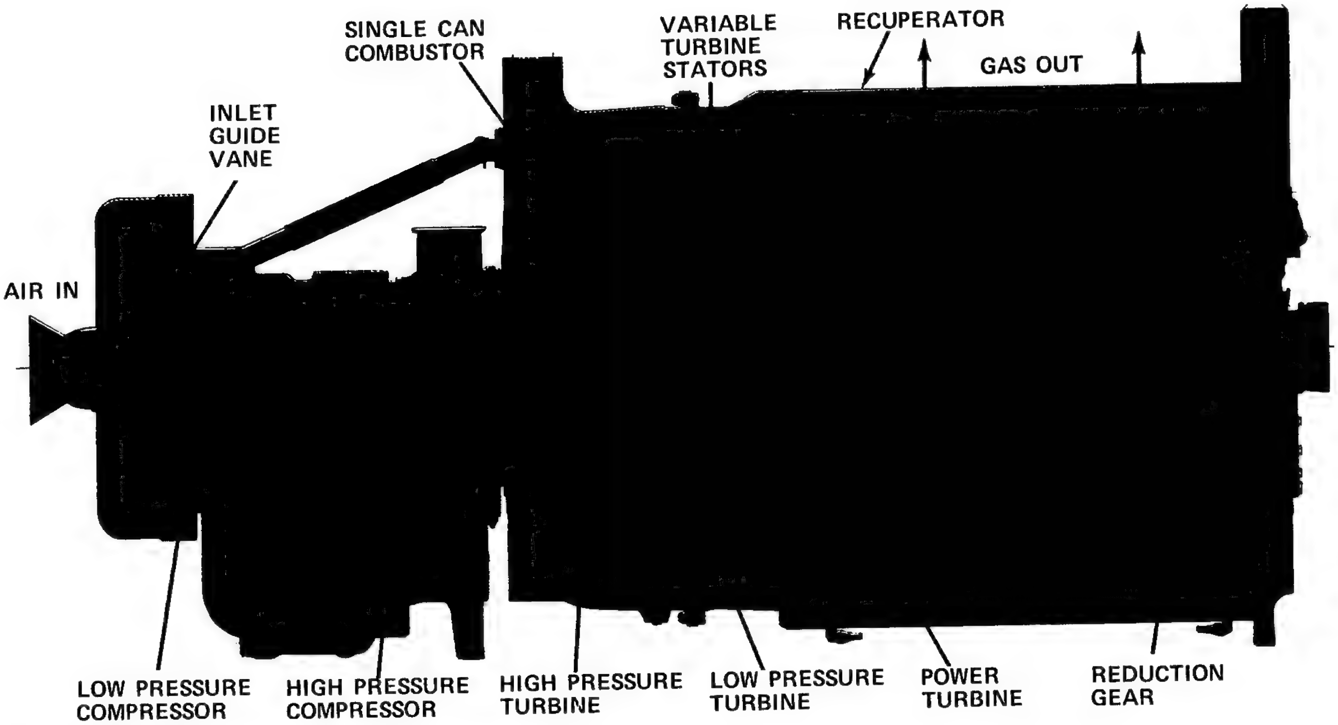


Figure 1

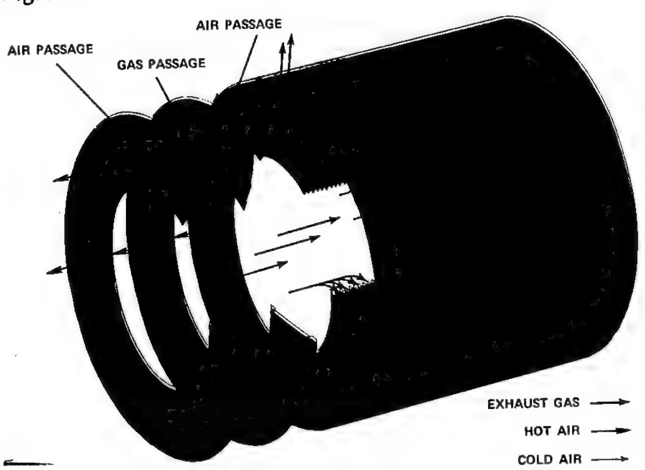


Figure 2

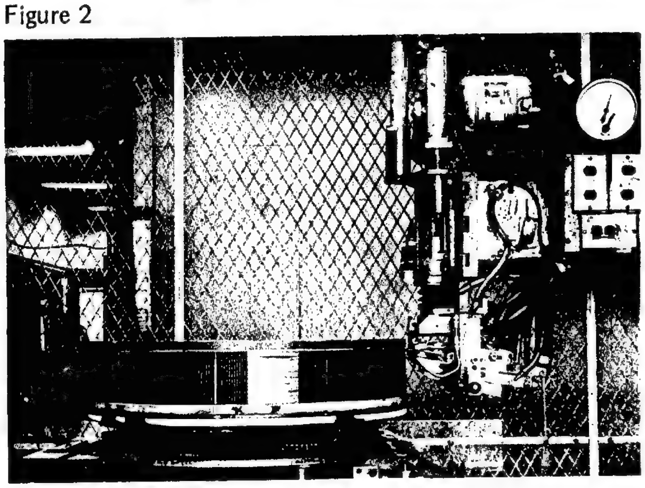


Figure 3

Complexity Multiplied

Avco Lycoming's AGT 1500 gas turbine is a recuperative engine with a multiwave plate recuperator which is an all primary surface heat exchanger made of thin convoluted metal plates. The exhaust from the power turbine enters the center of the annular recuperator where it diffuses and turns radially to flow through the recuperator (Figure 1). Compressor air enters the front of the recuperator into the air inlet holes, passes between the plates, and then leaves at the front of the recuperator via the air exit holes.

The AGT 1500 recuperator is sized to meet the performance goals of the engine over the entire operating range. The core is 22 inches long with an inside diameter of 15 inches and an outside diameter of 27 inches (Figure 2). The plates in the core are embossed with convolutions of two different geometries which space them at 0.040 inch and provide flow passages of suitable hydraulic diameter to achieve the desired effectiveness, pressure drops, and convolution stress levels. Because of the temperature and pressure levels encountered in the AGT 1500 engine, Inconel 625 was selected for the plates.

Indexing Time Slashed

The recuperator plates are hydroformed from 0.008 inch thick material and are first assembled in pairs by resistance welding around the air inlet and outlet holes (Figure 4). These two plates enclose the gas passages and have high pressure air bearing on the outside of them. Therefore, the hole welds are not highly stressed but only seal the air from the gas. About 290 pairs of plates are then assembled and welded around the outer and inner dia-

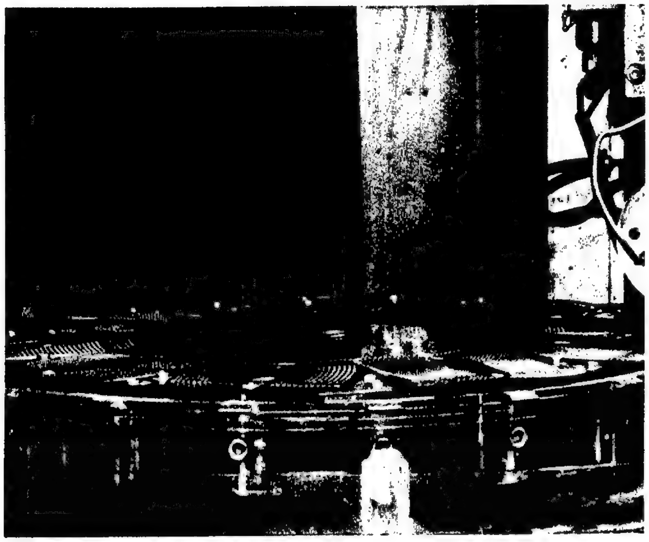


Figure 4

meters of the annulus to make a core. This welding operation encloses the air passages and serves once again to seal the air from the gas. The recuperator fabrication is completed by assembling and welding the header, followed by final pressure testing. With a total joint length of 10,000 feet per core, improvements in welding speed yield very substantial reductions in hardware cost.

The large number of short segmental welds required for joining the plates around the twenty air inlet and outlet holes per plate require extensive process time. Therefore, great cost saving results from reducing the indexing times and also increasing the welding speed. The somewhat complex hole shapes of the current design require accurate alignment of the electrodes along the curved sides of the holes. Dressing of the curved electrodes is also time consuming. In ID/OD welding, much time is spent aligning the electrodes with the joint and changing electrodes spent because of a high rate of wear.

Maintenance Reduced

Experience to date has shown that, although the resistance seam welding process is satisfactory for fabrication of plate type recuperators, current techniques require a large number of welding machines to meet production requirements, along with substantial maintenance support. In order to reduce welding time and cost, a program of screening and verification testing of various welding techniques was undertaken. The requirements established for the welding process were

- Low sensitivity to reasonable deviations in fitups and alignment of detail parts
- Reliability
- High speed of welding

Laser welding was selected as the most promising technique for accomplishing this improvement. It does not require contacting electrodes as does resistance welding, nor vacuum chambers, as does electron beam welding. And the laser is capable of high welding speeds.

Major benefits from applying laser welding can be derived from welding the air inlet and outlet holes alone. These welds comprise 60% of the total length of welds in the recuperator. Because they are short, interrupted welds with three or four passes per hole, they account for over 70% of the welding process time. Major effort therefore was concentrated on developing and testing laser welds for the hole peripheries.

The overall objective of the program was to minimize recuperator production costs through development and optimization of the welding process. Initial efforts of the program sought to develop the basic laser welding station concept, procure a laser welding system, design and manufacture a prototype welding station, establish optimum welding parameters, and prepare a preliminary analysis of laser versus resistance welding cost. In addition, the safety of the laser equipment was evaluated.

Laser System Design Selected

The requirement to weld thin plates around irregular geometries at high speeds dictated the criteria by which the laser system was selected and designed.

The laser welding machine had to be capable of continuous high output, and because the ultimate aim was for high volume production, it had to operate dependably with minimum maintenance. The system had to provide precise closed loop tracking of the air hole peripheries at these high speeds with no operator adjustments. Laser equipment currently available was evaluated to these requirements.

Commercial Unit Feasible

The first step in the selection of a machine was a survey of commercially available laser welders, their capabilities, and their costs. Since increased power means increased welding speed capability, the unit found to have the best potential for welding the AGT 1500 recuperator plates was a 2kw continuous output CO_2 laser manufactured by British Oxygen Company (BOC) Industrial Power Beams, Daventry, England. This unit is capable of producing 2000 watts at 100% duty cycle. The closest competing unit was only rated for 1500 watts maximum at less than 100% duty cycle. This system is composed of the main carbon dioxide laser generating equipment, the control console, the PDP 11/04 computer and teleprinter, a helium-neon laser for alignment, and the moving mirror system (Figure 5).

The laser generating equipment is divided between the main power cabinet and the laser bench itself. The power cabinet contains the gas mixing and control system, the electric power transformers, rectifiers, and associated controls. The laser bench has the lasing tubes mounted horizontally upon it. By using two 45 degree mirrors, the tubes are laid out in a U shape making the lasing path twice the length of the bench. Mounted under the bench are the vacuum pump, the Roots blower used to

circulate the gases through the tubes, and the catalytic recirculator and its ovens for reconditioning the gases (Figure 6).

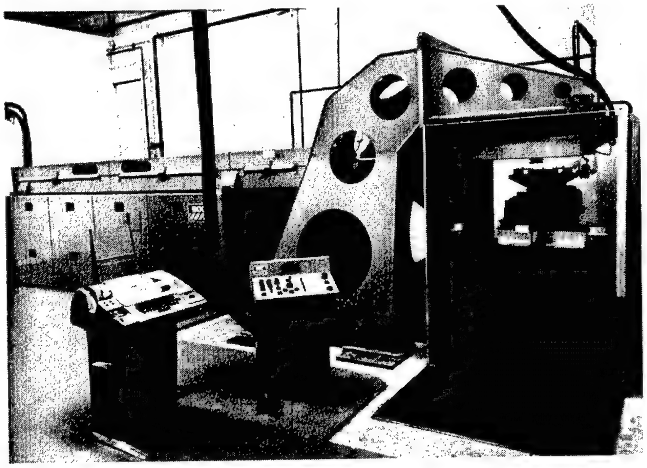


Figure 5

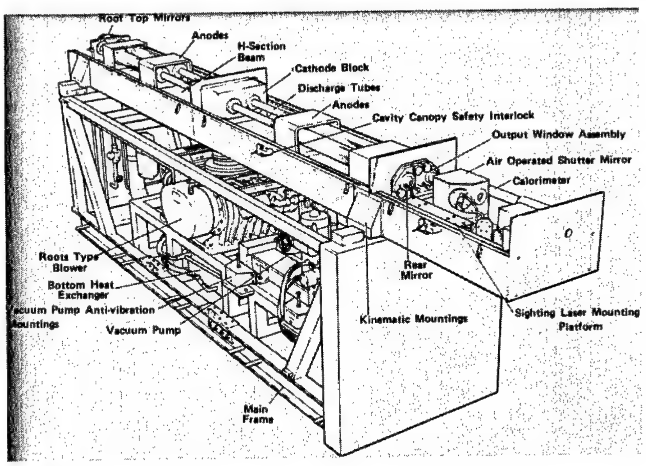


Figure 6

A shutter and mirror device downstream from the output window allows the beam to be directed into a refrigerated calorimeter when not passing through the output mirrors to the workpiece—that is, when it is in the beam off mode. The calorimeter monitors the laser output continually. A helium-neon laser is mounted in parallel with a prism, directing it down the precise path followed by the main carbon dioxide laser. The beam alignment and impact point may be checked with this beam of visible light. The prism assembly is interlocked so the main laser cannot be directed through the output mirrors while the low powered helium-neon laser is being used.

Segment Welds Superceded

An analysis of the high speed welding of the complex inlet and outlet hole periphery shapes showed the necessity of closed loop computer controlled manipulation. It further showed that the weight and, hence, the inertia of the necessary fixturing of the recuperator plates would be high. This made smooth, high speed joint tracking impossible if these were moved under a stationary beam. A system for manipulating the beam over a stationary part therefore was designed and built.

The output mirror assembly consists of two servomotor driven mirrors, an output nozzle containing the focusing lens, and associated welding gas and water cooling lines. The moving parts weigh less than ten pounds. By moving these two mirrors, the laser beam impact point can be moved to any location in a twelve inch square (Figure 7). The motion of these mirrors is controlled by a Digital Equipment Company PDP 11/04 computer which also controls the beam power. This system makes it possible to weld one pair of holes in a continuous high speed pass with the beam turned on and off as the impact point moves from one hole to the other.

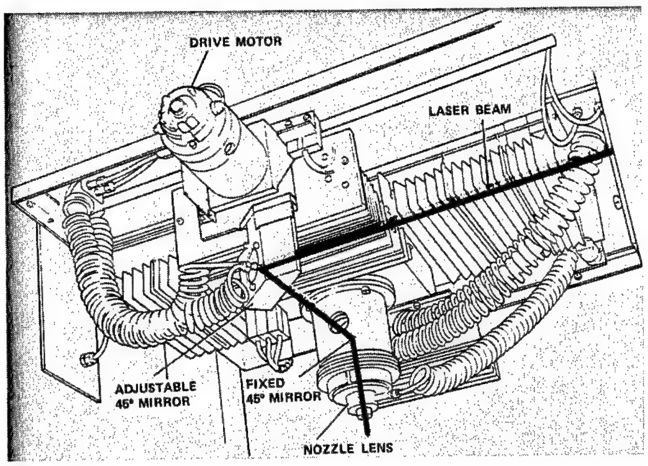


Figure 7

Indexing, Handling Computer Controlled

The complete welding station included not only the laser machine with the computer and related software to control it, but also the work handling equipment to position the parts and the tools to maintain the required contact between the parts at the weld joint. During welding the beam must track the hole peripheries; then, with the beam off, the beam impact point must be indexed to the next hole or group of holes. It was necessary to define the requirements for each of these functions, then decide which parts of the system would perform which function and how. An additional consideration was the requirement for a safety enclosure and interlocks.

Once it was decided that the recuperator holes would be welded in pairs by computer controlled laser beam manipulation, it followed that indexing between pairs had to be done by the tooling.

The prototype tooling is based upon a runout table which can be driven under the mirrors for welding and withdrawn for easy access when setting up or unloading. Mounted on this table is a "Rotab 36" precision positioner for indexing. In the prototype setup this is done manually, but this finction will also be computer controlled in the production welding station. Use of a separate positioner and table makes it possible to change the entire tooling setup if necessary for maintenance, or if a different type of positioner later is found to be required.

Mechanical Fixtures Most Practical

During work to develop the basic production tooling for maintaining the required contact between plate edges during welding, the least cumbersome method was found to be partial evacuation of the passages between the plates. In order to test the feasibility of this approach, a prototype setup was built. This consisted of a vacuum pump and tank to act as a vacuum reservoir and seals and ducting as required. The concept worked satisfactorily on recuperator test specimens because their simple, symmetrical shape and center access fitting made pump connection simple. When applied to full size recuperator plates, the problem of vacuum connection is much more difficult, since air must be evacuated from the plates at the edges. Removal of air at a sufficient rate to maintain necessary pressure differential at the edges of the holes remained a problem of such magnitude that mechanical fixtures were used to hold the plates together during welding. There were two alternatives for the basic design of the clamping arrangement. It was necessary to decide whether this tooling should maintain contact between the plates by bearing on the outer edge of the joint area or the inner side (Figure 8). The flat is 0.080 inch wide. It also was necessary to define the laser beam location.

The first approach tried was inside clamping. The weld track was 0.030 inch from the edge of the holes. Trial tooling for test specimens and for holding one set of recuperator holes was designed, built, and evaluated via trial welding. Figure 9 shows the fixture.

Figure 10 shows the recuperator plate fixture using this same approach. It eventually was eliminated due to insufficient heat sink between the weld track and the plate edge. This led to separation of the plates during welding and perforation of the top plate by the laser beam.

Based on these findings, new tooling was designed and built that clamps the part edges from the hole side. Figure 11 shows the fixture made to this concept for welding test specimens and Figure 12 shows the recuperator welding fixture. These fixtures clamp 0.030 inch of the edge of the weld land. Therefore, it was necessary to move the weld track to 0.050 inch from the edge. The computer program was changed accordingly.

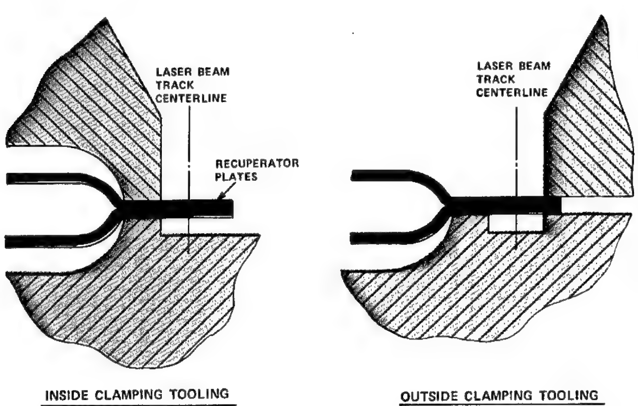


Figure 8

Safety: Door Interlocks

The support structure for the output mirror assembly was designed and procured separately by Lycoming. This structure provides the massive support needed to ensure repeatability of alignment and location of mirrors. It also supports the safety enclosure, again designed by Lycoming, which eliminates any possibility of injury by incorrectly reflected laser radiation. This enclosure has doors with interlocked switches to allow access only when

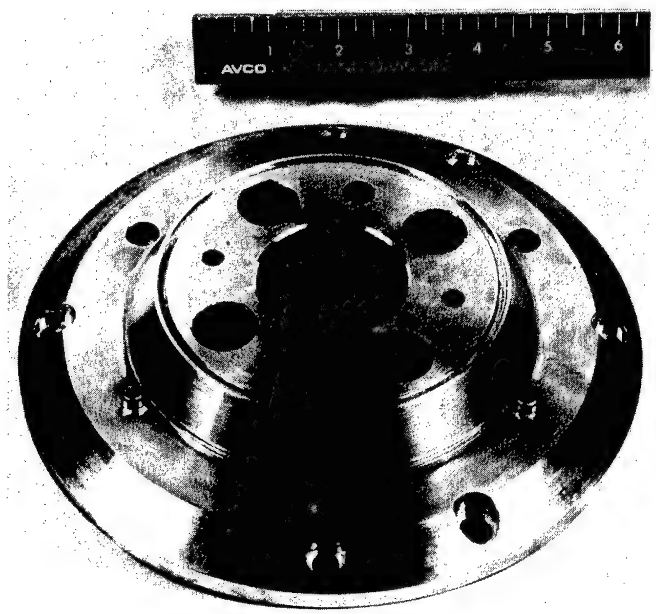


Figure 9

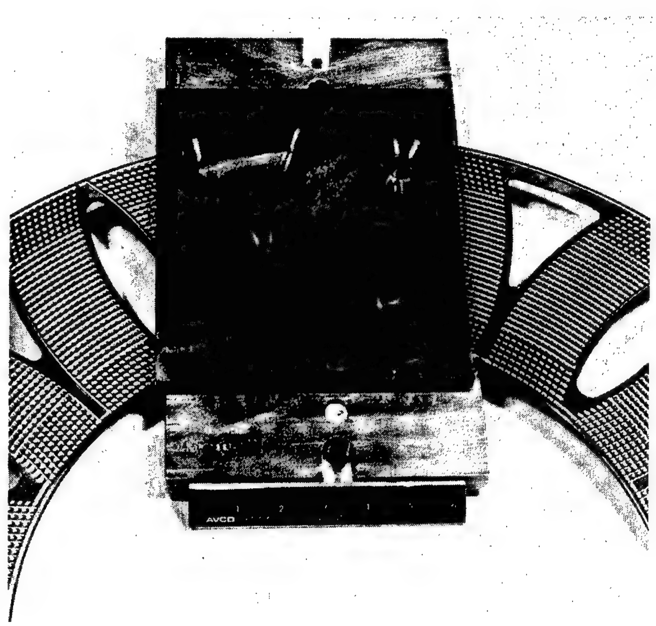


Figure 10

the beam is off (Figure 5). An analysis of the safety of the selected laser equipment was prepared and submitted separately from this report.

Computer Control System Developed

The computer program must guide the laser beam around the air inlet and outlet holes at high speeds, as well as control the beam on/off. As previously described, there is a 0.080 inch wide flat around each of the holes through which the welds joining two plates must be made. In order to have room for hold down tooling, it is necessary to precisely locate the weld track on this land. The initial geometry of the laser path selected for debugging the

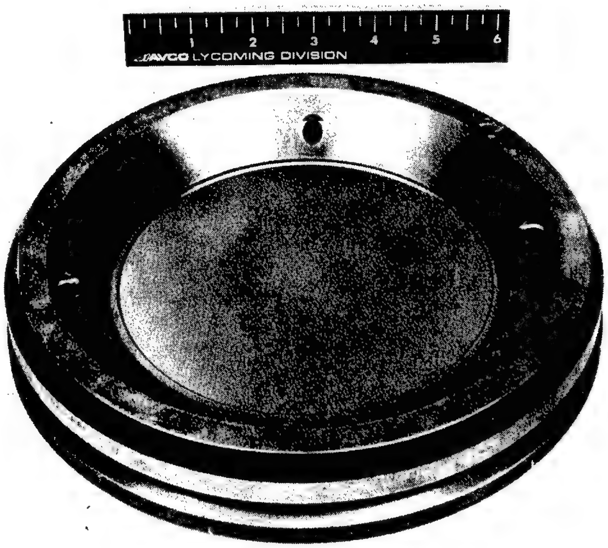


Figure 11

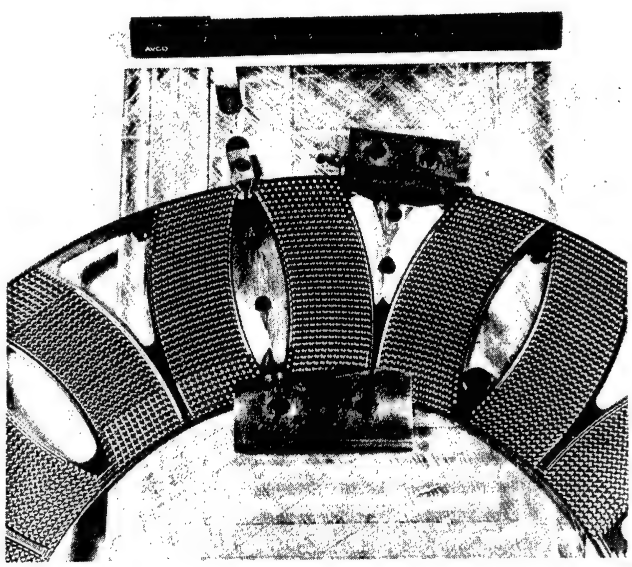


Figure 12

software was a straightsided triangle with 0.2 inch radius at each of the corners. This simpler shape (in comparison with the more complex actual shape of recuperator holes) was chosen to make the identification of programming errors easier.

The first tracking tests of the computer controlled mirror system indicated a ± 0.024 inch error band, much in excess of the beam path accuracy required. The software consisted of the welding program and the real time program which executes a list of commands defining the movement of the laser. Both programs are core resident. The straight lines and circular arcs defining a closed loop weld path are further subdivided by the program. All straight lines are subdivided into segments of 0.078 inch length. All circular arcs are subdivided into chords whose length can vary from 0.032 to 0.078 inch, depending upon the radius specified. The length of a chord is determined such that the maximum error between the circular arc and the chord subtending that arc cannot exceed 0.001 inch. Using this maximum allowable error as the controlling criteria, the radius defining the smallest arc should not exceed 0.195 inch.

Inacurracies Software Related

A review of the hardware and the software to find the cause of the inaccuracies indicated that many of the problems were software related. Basically, the software lacked an effective technique/algorithm by which a compensation factor could be calculated for the correction of any measured positional error in laser beam travel. At first, several methods were tried to compensate for the error obtained between actual and required beam position, but none were effective enough to achieve the desired accuracy. The movement of the laser beam is monitored via optical encoders which generate interrupts corresponding to 0.001 inch, the basic unit step of travel along each axis. In response to these interrupts, the program forms two sums which indicate the relative position of the beam expressed by its X, Y components. At the end of a given segment, a correction is made to the current velocity vectors based on the error calculated from its tracked displacement vectors. Subsequently, the following steps were taken to improve the accuracy:

- A program modification to pulse the velocity toward its correct path was inserted and a modification to vary the amount of compensation incorporated dependent on the increase in error since the last correction.
- Modification of the compensation system, taking into account the motor time constant. On tight, high speed curves especially the full effect of the last velocity change will not have occurred when the next compensation calculation is made.

With some minor additional program modifications, the positional errors of the beam path were reduced to an acceptable band of 0.04 inch for straight sides, but were still excessive ± 0.016 inch for the curved paths of 0.195 inch radii.

Intermittent Hardware Faults A Problem

At this point, effort was transferred from the straight sided triangle software to a program for the actual geometric shapes of the triangular and oval weld paths of the recuperator. The initial trials indicated some gross errors in the path, but following several corrections made to the program, an accuracy of ± 0.012 inch for the small radii was achieved. The beam on/off and slope up and slope down commands were also incorporated in the program. However, when this program was run repeatedly for the large number of trials required to verify its dependability for high volume production of recuperators, error aborts would occur with a frequency of 2 to 4 percent. This was not acceptable. By using photosensitive paper and the helium-neon laser, it was found that the repeatability of the track also was not acceptable.

A great deal of work was done to find and solve the causes of these discrepancies. A number of hardware faults were found and corrected. Among them were a defective teleprinter, a loose printed circuit board in the computer which caused an intermittent failure, and a water hose in the moving mirror system which sometimes dragged on a circuit board and bent it so it short circuited against the housing. An additional filter circuit also was added to reduce the amount of electrical ripple in the position sensing circuit. These problems, especially because of their intermittent nature, made the locating and correcting of software problems all the more difficult. However, work to overcome them continued, so dependable laser controlled recuperator plate hole welding at about 250 inches per minute could be accomplished. This speed is the maximum at which the system is designed to operate with reliability, and is determined by the time required for the sensors and computer to respond and correct the position along the weld track.

Laser Welding Parameters Defined

The required weld was defined as one made at high speed, having no cracks, porosity, or surface undercutting, and having low cycle fatigue strength at 1300 F equal at least to the resistance seam welds presently used.

The variables of the laser welding process are

- Power
- Travel speed
- Lens focal length
- Location of focus
- Welding gas selected and flow rate
- Tool design.

A single output lens focal length was selected on the basis of prior experience at the beginning of the program. Therefore, this parameter was constant during the investigation.

Power and speed and focal height were investigated, first by making trial welds on 0.016 inch thick Inconel 625, then on the double thickness of 0.008 inch from which the recuperator is made.

Both argon and helium were evaluated at various flow rates as welding gases. Work to develop welding parameters included optimization of tooling, part cleaning, and fitup requirements. Welds were evaluated by both destructive and nondestructive inspection techniques. These were used to evaluate the strength of laser weld as compared with resistance welds.

Welding Parameters Satisfactory

The 75-mm output lens was selected on the basis of the experience of BOC and preliminary work at the Bri-
the experience of BOC and preliminary work at the British Welding Institute and was treated as a constant. Power settings from 1000 to 2000 watts at approximately 100 watt intervals, location of focal spot from 0.010 below to 0.070 inch above the upper surface, and speeds from 200 to 500 inches per minute were evaluated. However, because the upper practical limit of welding speed dictated by the requirements of the computer program is about 250 inches per minute, effort was concentrated to find the optimum parameters at this speed. Both helium and argon were evaluated as welding gases, and gas flows from 10 to 80 cubic feet per hour were evaluated. Over fifty trial welds were made using various combinations of parameters. The optimum setting was found to be 1500 watts at 250 inches per minute. Focal point was 0.040 inch above the top surface of the joint and helium at 15 cubic feet per hour was the welding gas. Due to problems with the computer software described above, these welds all were made with a stationary beam and mechanical motion of the weld specimens.

Visual Inspection Effective

As in any development program, the greatest number of weld setting combinations were eliminated by visual inspection. Penetration was either incomplete or so heavy as to cause undercutting or perforation of one or both plates. Visual inspection of welds made with the optimum settings showed both the upper and under crown to be smooth and uniform with no undercutting (Figure 13).

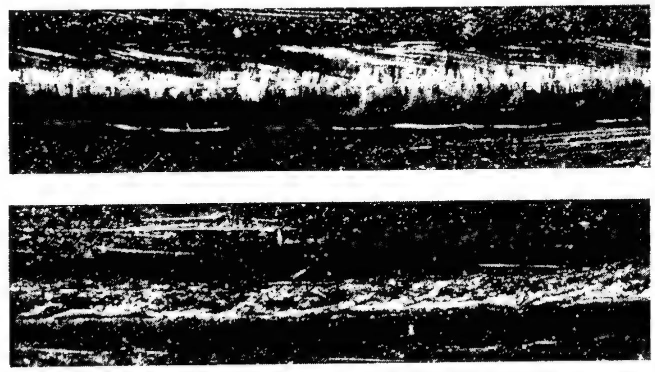


Figure 13

It is interesting to note that visual inspection of welds while investigating the effects of varying helium flow at the nozzle (welding gas) showed the same discoloration and oxidation with insufficient flow (below 8 cubic feet per hour) as with excessive flow (above 25 cubic feet per hour). Approximately five feet of weld made with the optimum setting was radiographically inspected and found to be completely defect free. These samples were also fluorescent penetrant inspected with the same result. Numerous microsections were prepared and examined through welds made with optimum setting. All showed a sound weld, with an interface width of about 0.016 inches. The top crown is about 0.021 wide, while the underbead is approximately the same width as the interface (Figure 14).

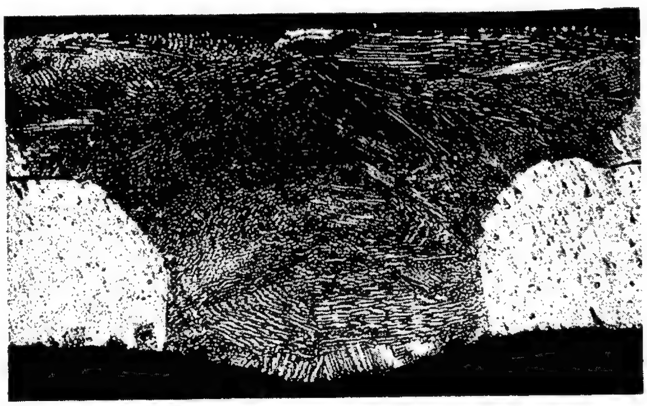


Figure 14

Laser welded specimens were tested in low cycle fatigue by internal pressurization at 1300 F at the British Welding Institute; these were settings similar to those developed in this program. The specimens were made with the BOC 2kw laser, the same as that purchased. These welds were made using moving tooling under a stationary beam at 240 inches per minute and at 288 inches per minute. The results are presented in Figure 15. The slightly larger scatter band for laser weld specimens is attributed to the specimens having been made under various parameter combinations.

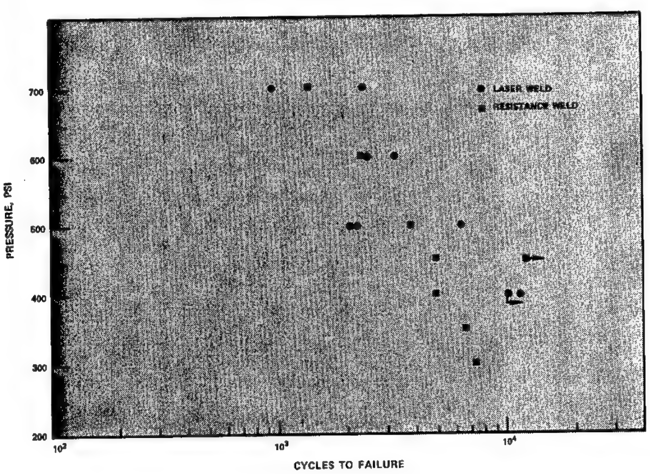


Figure 15

Weld Reliability Assured

Inspection of welds made during this program showed laser welding to be at least as reliable as resistance welding. Additionally, the constantly changing condition of welding electrodes, as they wear, is not a consideration in laser welding. For this reason, there appears to be no reason why laser welded recuperators would require more extensive inspection than is currently used on resistance welded assemblies—that is, a simple pressure test for leaks is all that is required.

Laser, Resistance Systems Costed

Based on information obtained, a preliminary cost analysis comparing laser welding to resistance seam welding for recuperator plates was prepared. This analysis compares a two laser machine welding station on which each machine performs one half the hole welds joining a pair of recuperator plates and the Sciaky Dialfeed System of eight resistance seam welders, each making some portion of the required welds. The laser weld speed of 250 inches per minute is the result of the work described here. The data for the resistance weld system was supplied by the equipment manufacturer. Since neither system has yet been applied to production, all costs, cycle times, etc., are estimates.

Cycle Times Compared

Each pair of holes is joined by 35.5 inches of weld. There are ten sets of holes per plate, and each laser welder would weld five of these at 250 inches per minute. The weld time per plate is therefore 0.7 minutes. It is necessary to index 5.5 inches five times between welds at an estimated 150 inches per minute. Index time is therefore 0.2 minutes. By using a two station dial feed fixture, one station could be loaded and unloaded while the other is being welded, so the only additional time required is 0.1 minute for dial feed index. The laser weld cycle time therefore is estimated at 1 minute per plate pair, floor to floor. One recuperator—290 pairs—would require 290 minutes for hole welding.

The eight machine system being built actually welds simultaneously with seven and uses the eighth as a spare in case of breakdown or required maintenance. The manufacturer estimates the cycle time at 1.5 minutes per pair. Added to this must be the time required to change electrode wheels every 3000 inches of weld. It is estimated that electrode change time per recuperator will be 70 minutes; one recuperator would therefore require 505 minutes for hole welding.

Laser Facility Needs Less

The laser systems are rated at 40 kvA input each, or 80 kvA input total. At 50% load cycle using electricity at $0.04/per hour, it would cost $19.00 for the electricity to

weld one recuperator. The seven resistance welders are rated at 50 kvA each. Using the same duty cycle and cost used for the laser, it would cost $146.00 for the electricity to weld one recuperator.

The two laser welders use 600 gallons of water per hour each, or 1200 gallons total. At $400.00 per million gallons, the water required to weld one recuperator would cost $4.56. The resistance welders use 300 gallons per hour each or 2100 gallons per hour for the seven. Cost of water to weld one recuperator is therefore $7.30.

Gases are the consumables of laser welding and the estimated cost to weld one recuperator is $74.34. Resistance welding electrode wheel costs are based on the price of the original blank and the cost of machining and redressing it through its useful life. This cost is estimated at $250 per recuperator.

Total Estimated Costs Summarized

Assuming a price for shop labor (factored and burdened) at $30.00 per hour the estimated costs are as follows:

Laser Welding

290 min. = 4.8 hours x $30 per man-hour	$145.00
Electricity	19.00
Water	2.40
Consumables	74.34
Total	$240.74

Resistance Welding

505 min. = 8.4 hours x $30 per man-hour	$252.00
Electricity	146.00
Water	7.30
Consumables	250.00
Total	$655.30

The estimated cost ratio is $655.30/$240.74 = 2.7, or a 63% reduction.

Achievements Reviewed

- This article describes the work done to develop improved manufacturing techniques for the AGT 1500 recuperator, a thin plate heat exchanger made by welding together about 580 convoluted plates 0.008 thick. There are over 10,000 feet of weld joining the plates, so improved higher speed welding techniques offer very significant cost reduction opportunities.

- Laser welding was selected as the most promising method for improvement over the currently used resistance seam welding.

- The laser machine selected for this application is a British Oxygen Corporation 2kw continuous output CO_2 laser with computer controlled moving output mirrors to permit high speed welding of the complex air passage periphery joints of the recuperator. Also designed and built were the output mirror support structure, prototype work handling and welding fixtures, and a safety enclosure.

- A computer program to weld the air conduit holes at high speed was written. Optimum weld settings were developed and the welds evaluated both destructively and nondestructively. A preliminary investigation showed the low cycle fatigue strength of laser welds to be equal to resistance welds when loaded by internal pressurization at 1300 F, the conditions encountered in the recuperator. The optimum setting for welding the recuperator plates is at a speed of 250 inches per minute, compared with an average of 50 inches per minute for resistance seam welding. Furthermore, each hole will be welded in one continuous pass, rather than several passes for each hole as in resistance welding.

- Fixturing requirements for laser welding thin plates were investigated and the optimum method found. Prototype tooling using this concept has been designed and procured. A preliminary cost comparison of laser versus resistance seam welding for the air duct hole welds showed a weld station of two laser welders to be capable of producing parts at the same rate as an eight machine resistance welding station at 63% less cost. It has been concluded that laser welding offers the potential of a substantial reduction in recuperator production cost.

- The welding of recuperator plates around the air inlet and outlet holes by laser is practical and substantially less expensive than via the presently used resistance seam welding procedure. Welding the passages by laser will potentially produce a cost reduction of approximately $400 per recuperator assembly.

- Work on the development of laser welding of recuperator plates is continuing.

Electrode Arc Length Monitored

Projectile Band Welds Automated

RONALD C. REEVE, JR., is President of Arc Systems, Inc., a Hebron, Ohio firm specializing in the development of automated arc welding processes and equipment; also, the supply of these systems to commercial welding firms and metal fabricators. Until August, 1979, he was Product Manager and General Manager of the Air Products and Chemistry (Arcair) plant in Lancaster, Ohio, where he coordinated and integrated the firm's R&D project conducted for Frankford Arsenal which resulted in the automated arc welding system described in the accompanying article. Mr. Reeve received his B.S. in Physics from Ohio State University in 1967 and his MBA from Xavier in 1972. He worked for General Electric for five years following his graduation as a research scientist on the growth of industrial diamonds. Then he joined Arcair, where he specialized in development of automated arc welding systems. He is a member of AWS, ASM, and the RIA branch of SME.

Editor's note: The automated arc welding system developed through the program described in this article marks a notable achievement of an Army MM&T project—the formation of an entire new company that is dedicated to the iteration and further development of the system. The original prototype system was delivered to Frankford Arsenal as a working machine in 1975, and since that time, the developer has marketed a commercial version and has delivered 18 systems to cladding firms. Arcair also invested its own money to improve the design and develop machine tools for production, marketing a more cost effective, new generation model featuring improved quality and reliability after completion of a deliberate value engineering study. This spinoff has now spawned a new firm, Arc Systems, Inc., a direct result of the development of a viable new system through an Army funded project.

Computerized automation is the solution turned to by Frankford Arsenal for the welding of nonferrous rotating bands on military projectiles. This process requires precise control of the welding procedure to meet the most stringent bonding conditions, and it previously required operators of the highest skill in order for the technique to be feasible.

In a project for Frankford conducted by the Arcair Company of Lancaster, Ohio, a new system of welding by gas metal arc was successfully designed, built, and tested which establishes a new level of proficiency in controlling the arc length of the welding electrode. This has been a most critical factor in the implementation of a practical automated system for performing this operation.

Nonferrous Rotating Bands Overlaid

The overlay technique is used instead of swaged bands for some military projectiles and provides a more secure bond than mechanical swaging. Rotating bands serve a dual purpose, since they act as an "obturator" and are engraved by the rifling while passing through the barrel, imparting spin to the projectile. Reliable bond is, therefore, essential to make sure that the bands do not loosen during firing. Welded overlaying also permits the design of shells with thinner walls than can be banded by swaging. The latter requires that a band blank be pressed into a machined band seat, resulting in a thicker wall.

Welded overlay bands previously have been deposited on artillery shells of a variety of sizes and designs. Some shells have a single band, while others have multiple bands. The width and height of the bands vary according to the shell design.

The process that was developed for producing the overlay made use of gas metal arc welding,—also commonly known as the metal inert gas process—with the addition auxiliary or cold wire in addition to the electrode wire. The use of cold wire makes it possible to add volatile alloying elements such as zinc, which will not transfer across the welding arc. Another important reason for adding cold wire is that it increases the amount of metal in the weld puddle and screens the shell from excess melting and intergranular attack. Adverse metallurgical effects can occur if this penetration is excessive.

Less Skill, Closer Control

Although rotating bands have been successfully welded on shells, the technique previously used clearly disclosed two problem areas. One of them was that in order to produce acceptable results, the intervention of a highly trained operator was frequently required. This is not always feasible in production operations. What was needed was an automatic system that would control the process parameters and compensate for in process variations that might occur.

The second problem was that the overlay process is more like a braze, where intimate interface bonding is required without mixing of overlay and base materials, unlike established procedures for fusion welding. This is harder to achieve than by fusion welding, and it requires very stringent controls.

Arc Length the Key

Experience with welded overlay banding shows that control of arc length during deposition is one of the chief factors in achieving uniformly acceptable quality of the rotating bands. Changes in arc length cause variations in intergranular penetration of the overlay material into the base metal, weld spatter, and surface pitting. It was determined that arc length should be maintained within 1/16 inch of the preset value to ensure optimum control of this intergranular penetration and weld spatter.

System Provides the Solution

The answer to the problems presented by overlay welding of bands was obvious—devise a system which would take advantage of technological advances in areas not previously considered to be related to welding and combine these with the latest improvements in welding power sources. This resulted in the marriage of microprocessor, photosensors, television equipment, and a linear slope control power supply to automate the entire welding cycle. There are no timers to set or knobs to be turned by the operator to adjust the electromechanical devices. All data is entered through the keyboard and all timing is done through the keyboard of a microprocessor, thus eliminating the possibility of operator error which could occur during manual settings. With a programmed sequence there can be no such errors. In this system a specially modified television camera monitors the length of the arc during welding and will control arc length within 1/16 inch over a range of 1/8 to 1 inch. The television measures the arc length visually and when the arc varies from an established standard, the microprocessor responds to the image change and effects the necessary changes to correct arc length. There are five possible ways available to control or maintain arc length:

- Power supply voltage change
- Power supply amperage change
- Wire feed speed
- Torch to work distance
- Combination of above in variable proportions.

The linear slope control is a unit which—when coupled with the television sensor and the microprocessor—rapidly makes corrections in the total voltage to maintain arc length or, with slope added, the amperage.

Five Parts Comprise Equipment

Overlaying is accomplished by rotating the projectile in a fixture beneath the welding head during metal deposition. The overlay material is provided by simultaneously feeding consumable electrode and nonelectrode auxiliary wire into the puddle. The overlay can be placed at any location along the axis of the projectile up to within ½ inch of either end. Oscillation when necessary is used to obtain the desired overlay width. A shell loading and unloading transfer mechanism can be connected at the front and rear of the welder to obtain a throughflow of parts for automated production. Shells up to 150 pounds in weight can be handled.

The system (Figure 1) consists of five general parts:

- Basic heavy operational equipment
- Welding equipment
- LSC power supply
- Shell cooling system
- Microprocessor.

The **main frame** contains a headstock, tailstock, and loading/unloading mechanism. The driven chuck in the headstock is axially fixed, while the nondriven chuck in the tailstock can be axially adjusted to accommodate shells of various lengths. The driven chuck is rotated by a dc stepper motor drive. To provide flexibility for all known artillery projectile applications, any rotation speed between 0.1 and 3 rpm can be obtained, either clockwise or counterclockwise. A pneumatic device actuates the axial movement of the nondriven chuck to advance the chuck and hold the shell, provide the holding force, and to retract the chuck at completion of the welding cycle. The headstock has provision for the shell cooling water tube and nozzle to pass through it into the shell cavity and to retract when the cycle is complete.

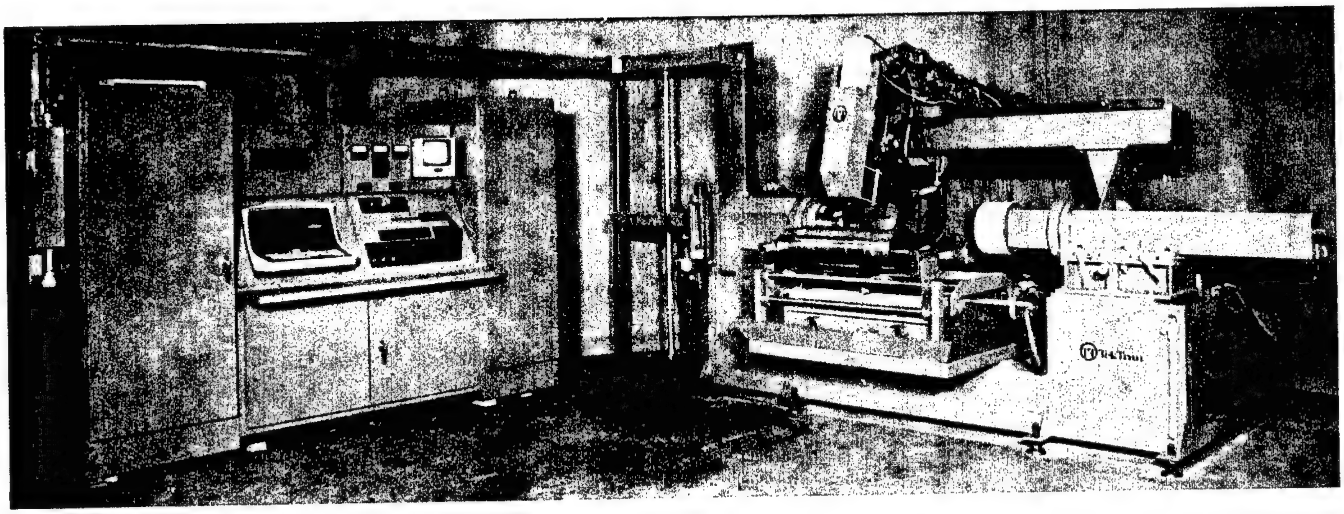


Figure 1

The loading mechanism will place the projectile in position for chucking. The shell is introduced below the centerline as shown in Figure 2 and then elevated to centerline and gripped in the chucks as shown in Figure 3.

The Linde ST-12 Mig **welding torch** (Figure 4) is water cooled. It contains a gas diffuser composed of a fine mesh wire which reduces gas turbulence and provides an exceptionally stable stream of shielding gas. Screw-in electrical contact tips are easily replaceable. The torch is insulated from the system by a dielectric insulating sleeve, and its cooling system functions independently of the shell cooling system.

Pure Bonds Desired

The metal inert gas welding process has enjoyed considerable growth in the past 30 years. The primary reason for this is that it lends itself to mechanization, permits high amperage welding and high rate of metal deposition. Suitable equipment has been developed to accomodate the needs of automatic machine welding. It is used not only to produce mechanically strong joints between parts, but often to deposit dissimilar metals for specific reasons such as hard surfacing, cladding steel with stainless steel for corrosion resistance, or for applying rotating bands on artillery shells.

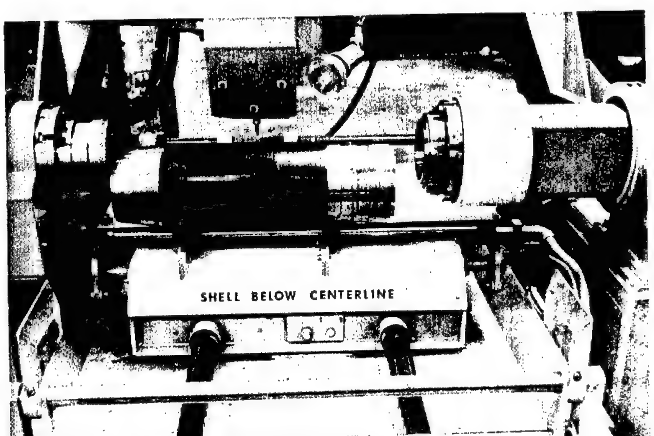


Figure 2

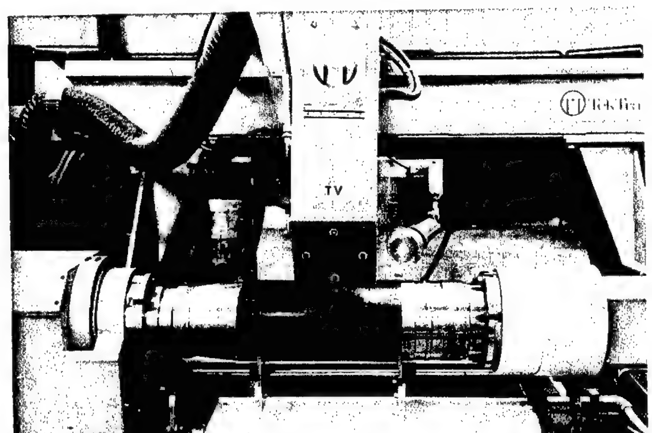


Figure 3

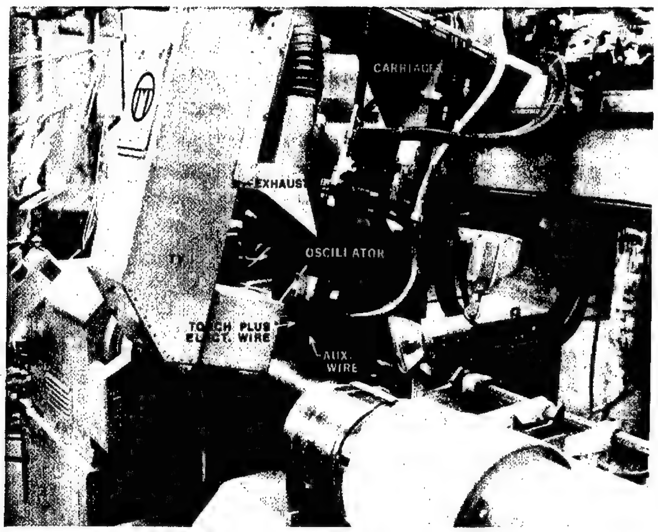


Figure 4

The requirements for producing a structurally strong joint are fundamentally different from the requirements for producing a satisfactory overlay. For a structural joint it is desirable to have deep penetration by the welding arc into the base metal, and good mixing between base metal and the electrode material. In the case of hard surfacing or overlay banding materials, any such mixing can have adverse metallurgical effects. The objective is to accomplish intimate bonding at the interface without intergranular penetration.

Little Advance Made

It may be assumed that in the age of space travel, welding technology kept pace with the technical innovation; however, a close look must be taken at some segments of the welding field. Certain segments such as those devoted to aluminum, titanium, zirconium, chromalloy, and other special materials advanced rapidly in power supply, welding control, and torch development. However, the field of metal inert gas welding has made little noticeable progress in the past ten years and has made virtually no penetration into some segments of the welding market place. One likely reason for this is that the specialized applications represented a small portion of the market and did not offer high volume incentives that would have encouraged manufacturers to assign special funds for development. The requirements for the general welding industry, which represents about 85% of the market, have been met more or less at an acceptable economic level.

This does not mean, however, that all of the requirements of the general welding industry are being satisfied. Welding fabricators must accept some of the shortcomings of the presently available equipment. There are three areas which can be recognized as presenting serious limitations in GMAW welding:

- Inflexible power supplies
- Insufficient control of power supplies
- Lack of system approach.

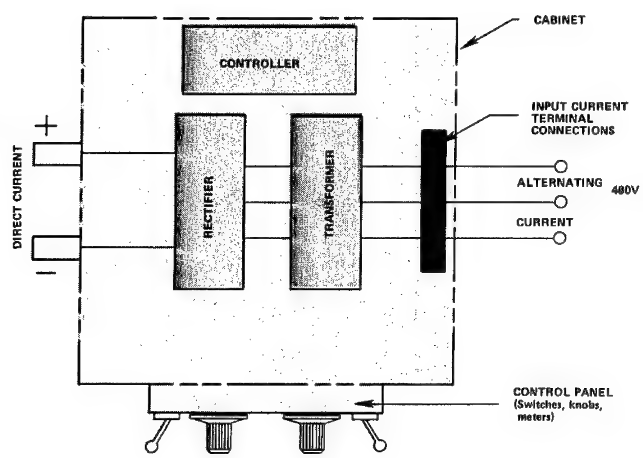


Figure 5

Linear Slope Control Totally Flexible

Much of the success of this system is due to the use of the novel linear slope control power supply (Figure 5). The fact that this unit is a solid state, electronic piece of equipment makes possible the successful hookup of power source, television monitor, and microprocessor. With the advancement of electronic technology it became economically feasible to consider taking a serious look at the state of power supply design with the idea of breaking with tradition in order to solve some of the long prevailing problems. As a result the new power source was developed which permits control of linear slope, the volt/amperage characteristic of any given power supply.

This power supply has an unlimited number of slopes with an unlimited number of characteristics. It can be either constant potential or constant current source or any mix in between those extremes. This is a flexible power supply. It makes use of "closed loop" control, which checks the actual voltage and current flow at the

terminals and compares them with the values set with the control dials.

The control fully compensates for line voltage variations up to ± 10%. The power supply is insensitive to ambient temperature condition. It is only concerned with output and will automatically adjust the output to desired level regardless of temperature. It is a fully electronic, solid state design having the benefits of electronics speed and accuracy—it can be commanded to change its output in 1/20 second. Because it is programmable, it is compatible with other electronic controls and lends itself to system design.

Electrode Variations Bear Impact

The contact tube in the welding torch through which the current is passed to the welding electrode wire is shown in Figure 6. The length of this tube varies with torch manufacturers and is generally between 2-8 inches in length. For a 1/16 (0.062) inch diameter wire the hole through the tube is in the order of 0.085-0.090 inch in diameter. Experience has shown that a tighter hole does not improve current passage from tube to wire.

Traditionally, arc voltage has been considered as determining arc length. The power supply voltage might read 22 volts during welding. This, however, is not arc voltage but rather the total voltage between the point where the wire picks up the current and the bottom of the arc (workpiece). This is shown in Figure 7. What part of the 22 volt reading on the voltmeter is heating the wire and what part of it is maintaining the arc are unknown factors because they are continually changing. The wire can be picking up the current in a six inch long contact tube right at the point of entry, or at the point of exit, or anyplace in between. Arc length varies continually; as the contact tube wears, the arc becomes more erratic and the control of the welder becomes more critical. Various metals have different resistance to the flow of electric current. If the composition of the weld wire changes so does its electrical resistance. A primary cause of change in surface resistance of weld electrode wire is the surface quality of the wire. Contamination of the exterior of the wire can be an important cause of arc voltage variation. The effect of voltage drop brought about by the changed resistance is a change in arc voltage and hence arc length. The only way to compensate for changing voltage drop is to adjust the output voltage of the power supply. It is preferable that this be done automatically.

Visual Technique Applied

The importance of arc length in the overlay operation can be clearly demonstrated. It is desirable to have a minimum of mixing or intergranular penetration of the overlay into the base metal. To achieve this, it is necessary to control energy input to provide sufficient heat to melt electrode and auxiliary wire and heat the outer layer of base metal to the melting point of the overlay material to ensure intermetallic bonding without actual mixing of the two metals.

Figure 8 demonstrates what happens when arc length varies. With a shorter arc, the heat is concentrated in a smaller area. When the same amount of energy is concentrated in a smaller area the temperature will be higher and

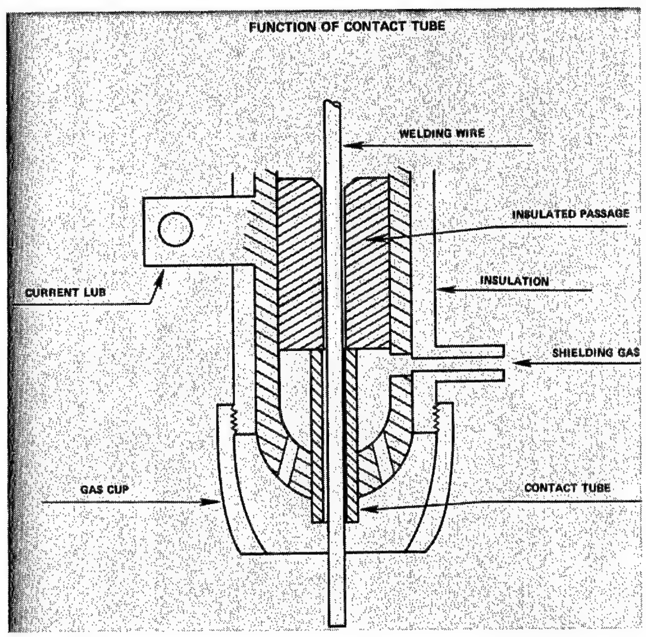


Figure 6

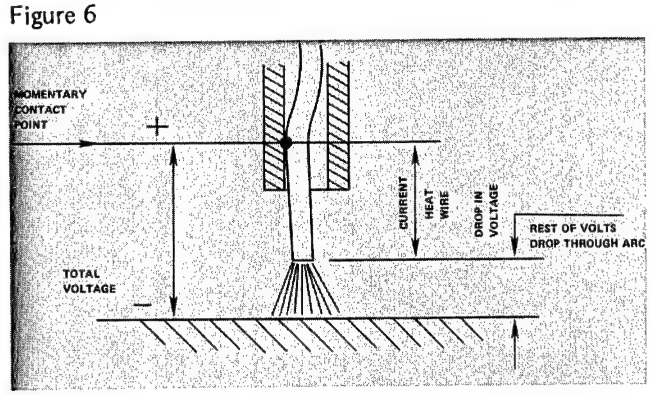


Figure 7

the base metal will get hotter. The arc digs in and deeply penetrates the shell and results in iron dilution in the copper overlay. If arc length increases, energy is dissipated over a larger area. The arc is "soft" and the result is insufficiently heated shell surface. The thermal changes are significant, yet the voltmeter reading can be identical.

Optical devices and television cameras previously have been used to view the arc during welding, but until this new system was developed, none had been adapted for controlling arc length.

The **shielding gas** used is a mixture of welding grade argon—99% argon + 1% oxygen. The contents of two gas cylinders are mixed to provide approximately 99.8% argon and 0.2% oxygen. The two cylinder system is preferred to a premixed supply since adjustment in mixture is necessary from time to time to accomodate different batches of wire. The introduction of a small amount of oxygen helps to prevent spitting or spattering of the wire during welding. The torch gas nozzle provides gas flow to adequately shield the arc, the ends of the electrode and auxiliary wire, and the molten puddle of weld metal from the atmosphere.

Heat Transfer at Weld Points

Internal water cooling is used at points corresponding to the location of the rotating bands to extract heat and so prevent overheating of the interface. Provision for shell cooling in this system is accomplished by a nozzle which extends from the headstock to its previously determined position at the band area inside the shell and then retracts when the weld cycle is completed. Figure 9 shows water nozzle extended.

The system has a Bernard 800 water cooler (Figure 10), a high capacity heat exchanger type that provides maximum heat dissipation in a minimum of space. By use of the limit switch provided, the system can be rendered incapable of striking an arc until the water nozzle and projectile are in position and shell cooling water is flowing.

Upon completion of the weld the nozzle will retract automatically to permit unloading of the shell. After the next shell is loaded into the welding station the nozzle will automatically be extended into the shell in such a manner that it is located at its predetermined position under the band location.

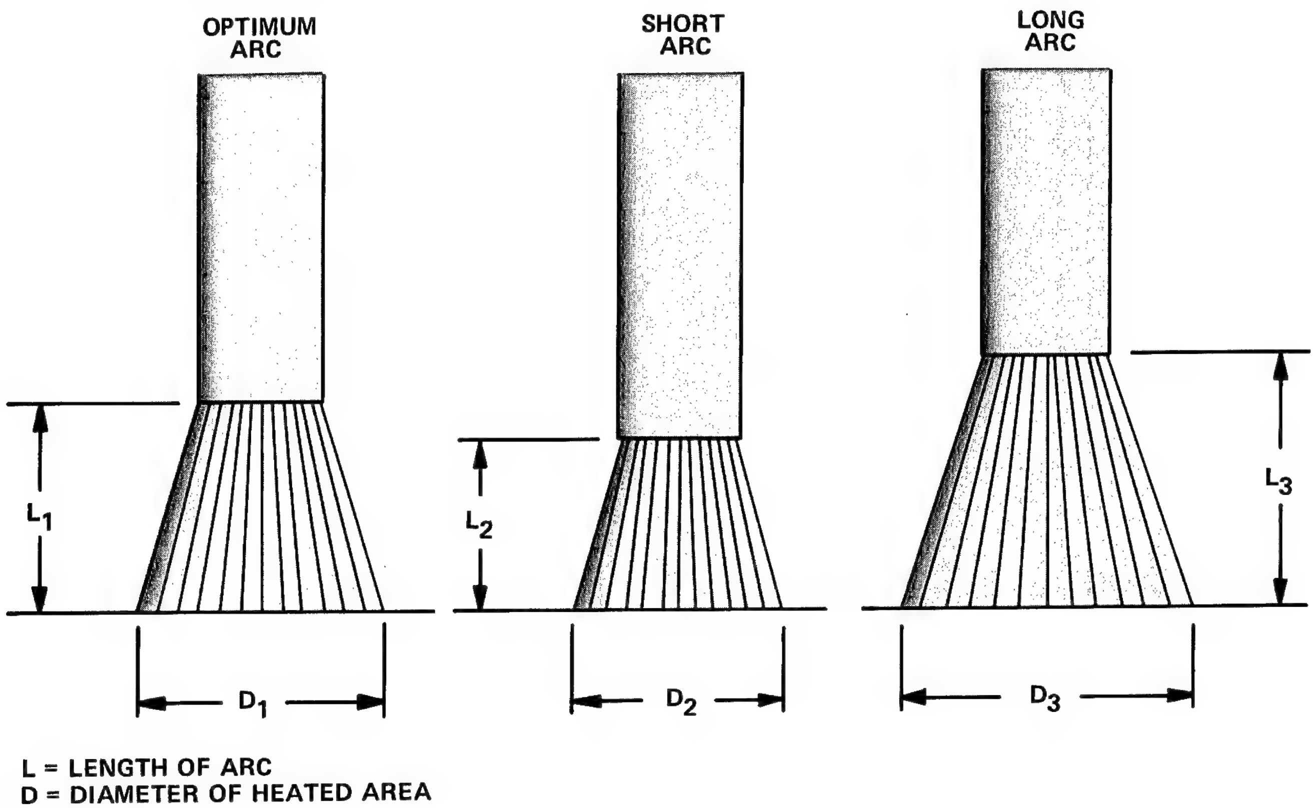


Figure 8

The Icing On the Cake

The incorporation of a microprocessor in the system offers the possibility of controlling many parameters simultaneously in an interrelated manner, monitoring and supervising other important functions, initiating time and sequence, and providing management information if and when desired. It can be programmed to communicate directly with the operator to send messages in English pertinent to the cause of trouble.

All of the process functions are monitored and controlled through a microprocessor which controls or monitors the following parameters:

- Shell rotation speed
- Torch oscillation frequency
- Torch oscillation amplitude
- Weld current
- Arc voltage
- Electrode wire feed
- Auxiliary wire feed
- Supply of wire
- Shell cooling water flow rate.

The television camera monitors arc length during welding and the output is fed into the microprocessor, which then directs the action of the power supply.

The microprocessor can adjust all of the parameters for all different shell sizes, and its memory has the ability to retain ten different welding schedules, any one of which can be recalled for use by demand at the keyboard. Cassettes containing various weld schedules can be stored and then selected for use whenever that particular schedule is needed again. The proper cassette is simply removed from its storage place and inserted into the microprocessor.

There are three modes of control built into the system:

- **Setup Mode**—The operator has full operations control of the welder and can run through all the motions or can adjust the torch, etc., but cannot weld.

- **Manual Mode**—The operator can experiment with different welding parameters and can perform actual welds or tests. This mode can be used to develop the actual production run automatic schedule.

- **Automatic Mode**—The welding operation is under fully programmed control with television feedback.

In automatic mode, if one of the parameters deviated from the set value beyond a permissible tolerance the microprocessor performs an orderly shutdown and displays the reason in English on the keyboard picture screen.

This microprocessor can be programmed to run two welding systems simultaneously. By use of supplied programming instructions, anyone can program this system by following a simple procedure.

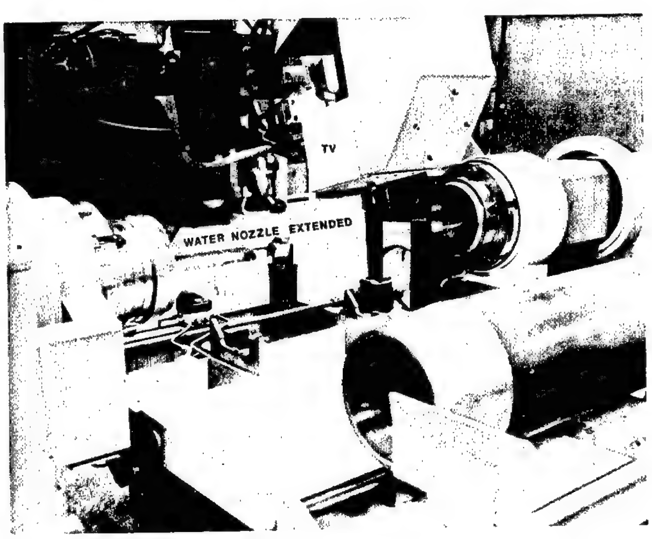


Figure 9

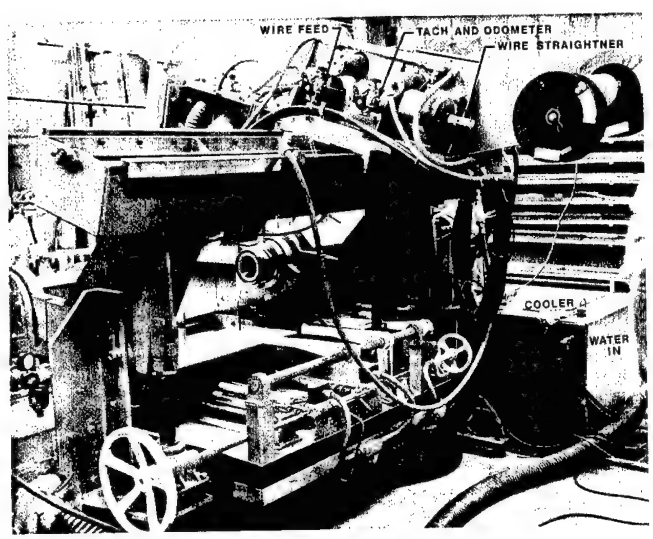


Figure 10

New Torsion Bars Carry Load

VAR Steels Selected

New designs for the Army's Armored Personnel Carrier and Infantry Fighting Vehicle have presented a special manufacturing engineering challenge for the company supplying suspension systems for these units. That company—the FMC Corporation—has completed the first part of a thorough research and development program (with notable results) on high strength torsion bar assemblies that is going to fulfill the new requirements. At the same time, their findings will provide considerable savings in the manufacture of these components. The project was conducted for the Army's Materials and Mechanics Research Center, Watertown, Massachusetts.

Designing suspension springs for Army track vehicles long has been a problem as the load per bar and the maximum wheel travel have both increased. To provide for these new requirements, it has been necessary to use a bar and tube assembly. The bar and tube assembly is costly, increases vehicle weight, and takes up more space than a single high strength bar. FMC presently is involved in the development of two new suspension systems for the M113A1 and the XM2 vehicles. The bars must have an endurance life of 45,000 cycles for a stress range of 20,000 to 160,000 shear stress on the M113A1 and 30,000 to 180,000 psi for the XM2.

The M113A1 is the standard Armored Personnel Carrier and the XM2 is the new Infantry Fighting Vehicle. It is

DONALD L. GIBSON is a Senior Staff Engineer for FMC Corporation in San Jose, California, where he has been principal investigator on the Army's work on high strength torsion bars for the M113 and XM2 combat vehicle suspension systems. During his 29 years at FMC, Mr. Gibson has worked extensively on these vehicles in addition to the Army's M75 and M59 personnel carriers and XM800 scout vehicle. He also has worked on the Navy's P7 tracked landing vehicle and numerous other wheeled and tracked vehicles for the Army, Navy, and Marine Corps. He was trained as a mechanical engineer at San Jose State and served as a pilot in the Air Force. He is an active member of the ADPA.

DINO J. PAPETTI is a Materials Engineer for the U. S. Army Materials and Mechanics Research Center, Watertown, Massachusetts. Since joining AMMRC in 1965, he has been active in exploratory development, advanced development, and prototype technical studies of materials for applications to a wide variety of end items, including aircraft, combat vehicles, and special purpose vehicles. Mr. Papetti was the recipient of the Army R&D Achievement Award in 1976. He received his B.S. in Mechanical Engineering in 1957 from Northeastern University.

a fairly light vehicle, weighing 26,000 pounds, while the new XM2 weighs 50,000 pounds. The torsion bar for the M113A1 is restricted because it must be usable in the refit of older machines; therefore, the spline size cannot be increased to cover the increased load of the heavier vehicle. The XM2, however, being a new machine, can use bars with large splines consistent with the high torque. The M113A1 and XM2 are shown in Figures 1 and 2, respectively.

Several materials were investigated during this program. The Army's primary objective in the program was to look at ESR steels. However, FMC had several programs going to develop the torsion bars for the upgraded M113/M113A2 and the new XM2. Consequently, it was possible to bring all of this data to bear on the AMMRC program. The tests were carried out on full diameter bars—either half or full length—as in the case of the XM2 bars.

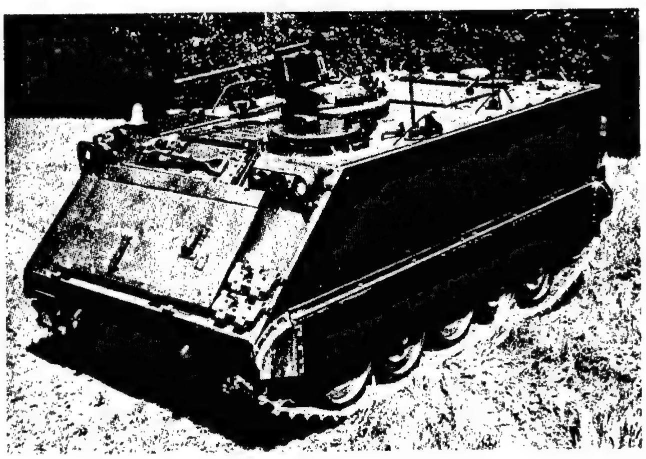


Figure 1

Figure 2

Program Results Change Direction

The prime purpose of this program was to develop high strength torsion bars for Army applications. Although the program started out to investigate ESR steels, a majority of the effort was directed toward evaluating alternate materials. The desirable material properties are as follows:

- High tensile strength
- Lack of low temperature temper embrittlement
- Fracture toughness as high as possible.

These properties unfortunately were not optimum in the ESR materials tested (4353 and 4357). The 300M steel appears to be the best compromise, and it probably would behave as well or better if prepared by ESR instead of VAR.

The prime material at the beginning of the program was 4353 Electroslag Remelted (ESR) steel; however, low temperature embrittlement was observed and it was decided that other materials would be investigated, such as Vacuum Arc Remelted (VAR) 300M and HP 310 alloy steels. These materials have mechanical properties similar to the 4340 class of steels, but have improved fracture toughness. Through the use of laboratory test bars, scaled down vehicle's torsion bars, and full size bars, all aspects of fabrication from material procurement to the vehicle test of the completed bar were investigated. This information was needed to write a specification to cover the new high strength torsion bars.

Price Change Has Impact

During the course of this program, the price of ESR steel increased to more than $2 per pound, compared with approximately $1 per pound for VAR (300M), so it would appear that there is no advantage in continuing to investigate ESR at this time. As more experience is gained in the processing and use of ESR steels and their cost decreases, they may again be possible candidates for torsion bars.

The 300M bars appear to be satisfactory for present applications, but it is apparent that a proper spline to body ratio is imperative. This would ensure greater bar life and prevent failure in the splines, which makes replacement difficult and also damages interfacing components.

Shot peening also is very important and therefore must be controlled to provide the maximum advantage without damaging the bar. Shot hardness, shape, and size must be tailored for each application. The most dramatic improvement was demonstrated in the test of the induction hardened bars. One example of what appeared to be excessive peening was experienced; a bar failed from a crack initiated in the white layer just under the peen affected surface. The latest thinking on this phenomena, which has been observed by numerous people in various applica-

tions, is that the carbon goes back into solution as a result of adiabatic heating and quenches to untempered martensite. Scratch testing indicates that the material is as hard or harder than adjacent structure.

Induction hardening appears to be another viable method of production for high strength torsion bars. It provides one advantage that is not possible in a through hardened bar—while a through hardened bar can be prestressed in the body, the beneficial precompression of the surface cannot be achieved on the splines. Induction hardening induces high residual compressive stresses on the spline as well as the body surfaces. Preliminary fatigue data on bars processed in this manner show that these bars provide acceptable life values, with no failures initiating in the splines.

Materials, Needs Varied

At the onset of this program, it was not clear what material parameters were the most important. The most likely candidates were yield and ultimate strength, impact characteristics, and fracture toughness criteria. Of course, processing parameters were also important. Therefore, some questions had to be resolved. Should the splines be machined or rolled? What kind of shot peening should be used, if any? How should the bar be preset to prevent creep (relaxation during testing) in use? This program has not resolved all of these questions, but the test results point out the importance of proper processing to maximize mechanical properties.

Each material investigated was considered separately and the results compared. All initial test bars were made with the M113 spline and various bar diameters to represent different applications. All of the materials were characterized chemically and mechanically. The 4353 ESR steel tested was supplied by Simonds Steel, Lockport, New York, and represented a full 30,000 pound heat. The HP 310 from Republic Steel also represented a full heat, but a smaller one of 2500 pounds. The 300M was purchased from Alley-Fry warehouse and the ESR 4357 was supplied by Cockerill in Belgium, all reportedly from the same heat. The 300M and HP 310 both were vacuum arc remelted steels.

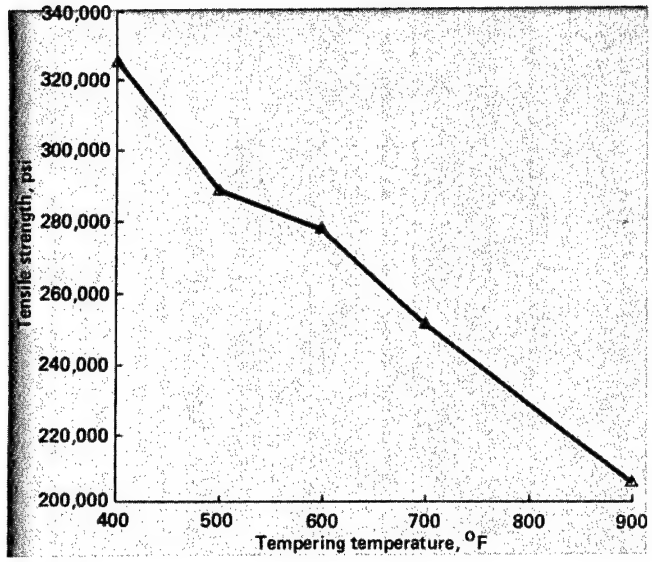


Figure 3

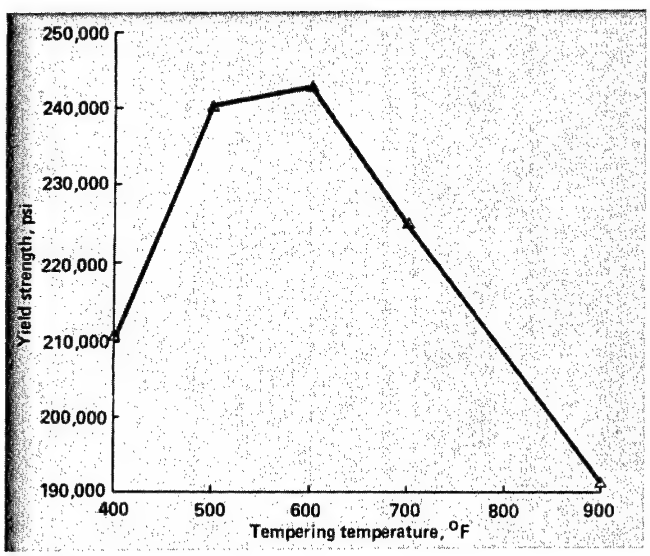


Figure 4

A Look At ESR Steel

The ultimate tensile strength of 4353 ESR steel as a function of tempering temperature (based on five test bars) is shown in Figure 3. The effect of double tempering was investigated and did not appear significant, so subsequent bars were normalized, quenched, and tempered.

The yield strength as a function of tempering temperature (based on five bars) is shown in Figure 4. The Charpy V-notch values as a function of tempering temperature (based on ten bars) are shown in Figure 5. The corresponding Charpy V-notch impact strength versus specimen hardness is given in Figure 6. When observing the data, a very definite decline in impact properties is seen in the range from 400 to 600 F. A large increase in yield strength also is seen.

To investigate torsional properties, a series of torsional stress strain tests were conducted with bars tempered to three hardnesses. The torsion test bars were constructed as shown in Figure 7. Torsional ultimate strength versus hardness is shown in Figure 8, and the torsional yield strength versus hardness is shown in Figure 9. The torsional stress strain curve for a hardness of 58 Rc is shown in Figure 10. As a result of the various tests, a compromise

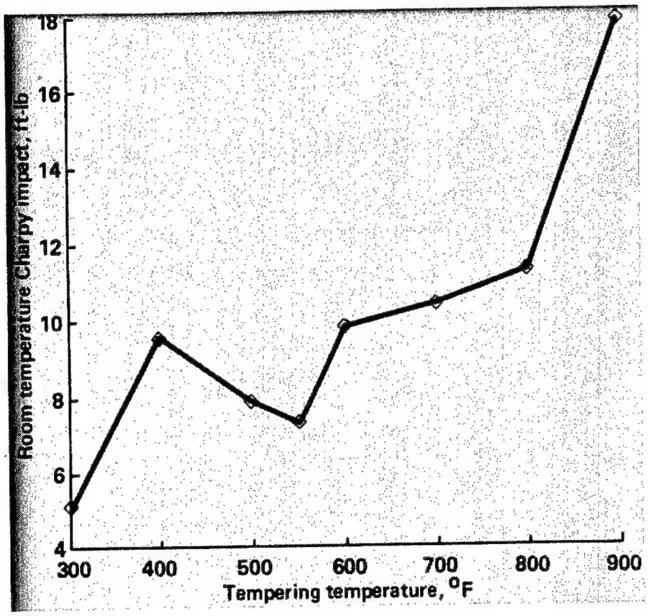


Figure 5

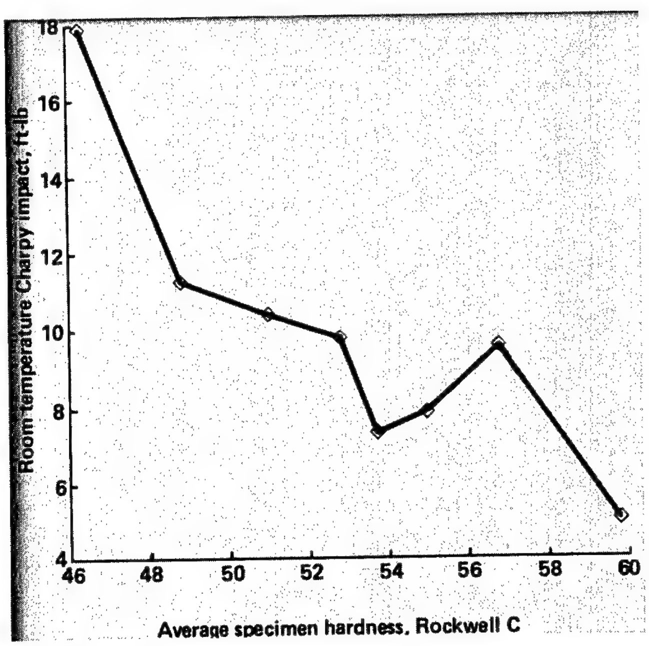


Figure 6

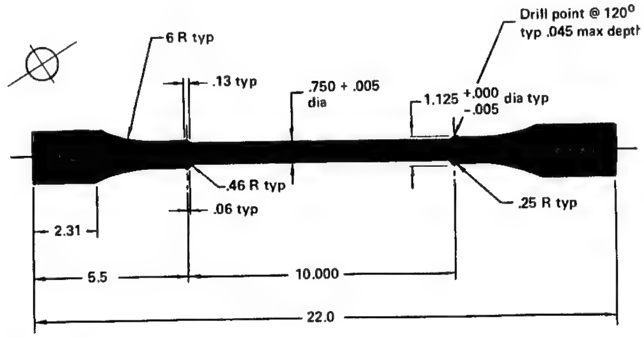


Figure 7

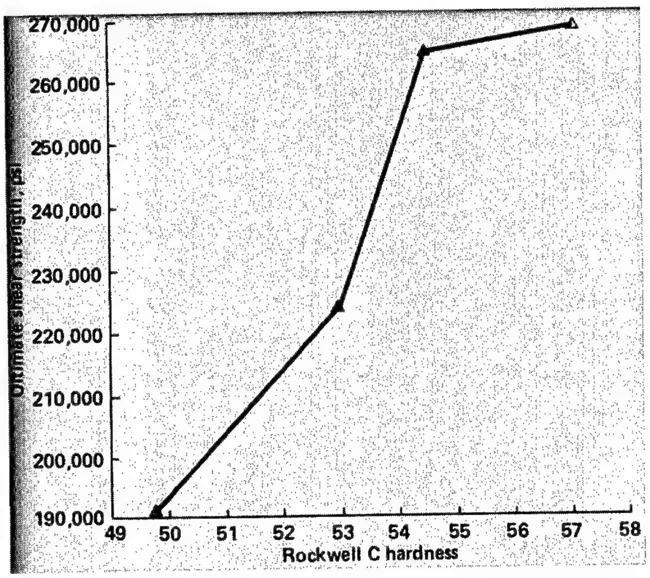


Figure 8

on the yield strength was decided upon—to temper the bars at 400 F.

Half length bars were fatigue tested in the M113 and the XM2 configurations. The results of these endurance tests are shown in Table 1. All bars tested had the M113 spline, and the body diameter was varied to produce the correct spline to body ratio for the two configurations.

The equipment used to test these bars is shown in Figure 11. The preset for M113 bars was 180 ksi, and it was 190 ksi for XM2 bars. The relaxation during testing (creep) is an important operational factor—typical relaxation data obtained during fatigue testing is shown in Figure 12. In all of the tests reported, the relaxation of the bars was within vehicle specification limits.

ESR 4353 Impractical

Analysis of the data in Table 1 indicates that the material is satisfactory in the XM2 configuration, but very marginal in the M113 configuration. Testing of full length XM2 bars tempered to 550 F yielded poorer results. The most discouraging fact was that the failures were essentially all in the spline, except for the one that ran over 600,000 cycles. The indication is that the material would be adequate for high strength bars, but because of the predominance of spline failures, the spline/body ratio

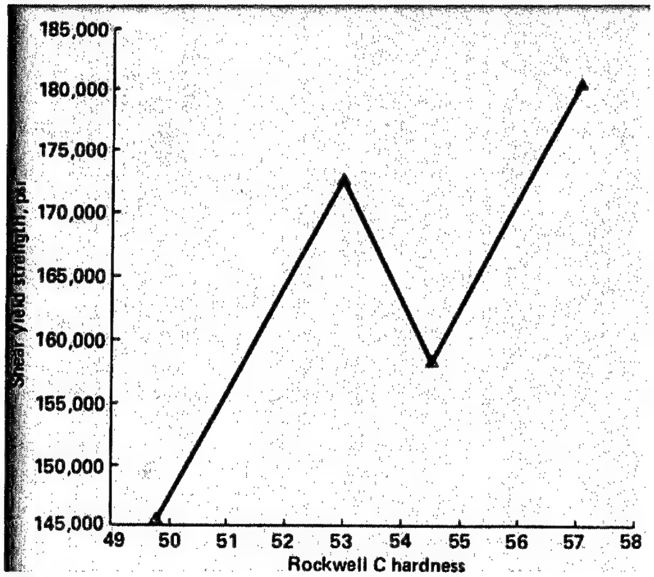


Figure 9

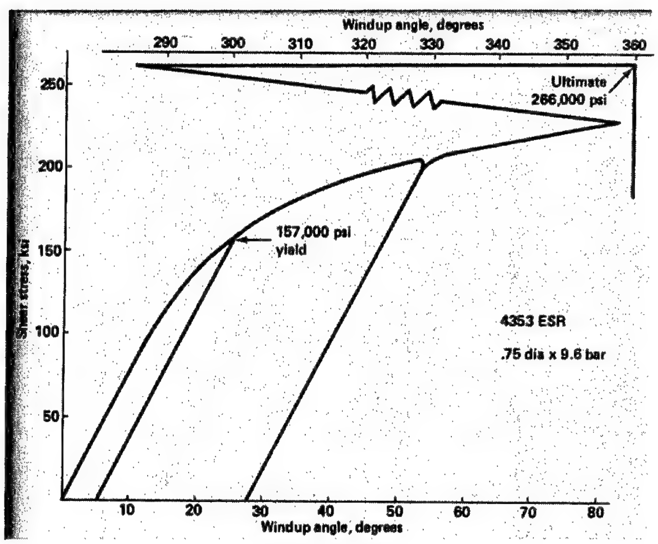


Figure 10

(New Torsion Bars)

Material	Body Diameter, in.	Stress Range, ksi	Effective Length, in.	Cycles to Failure	Location of Failure Initiation	Tempering Temp., F
4353 ESR	1.30	21-175	27.3	83,280	Spline	400
	1.30	20-160	27.3	82,210	Spline	400
	1.30	20-160	27.3	83,380	Spline	400
XM2	1.30	20-160	27.3	671,310	Body	400
	1.30	20-160	27.3	93,150	Spline	400
	1.35	45-180	59.28	53,100	Spline	550
	1.35	45-180	59.28	85,700	Spline	550
	1.35	45-180	59.28	45,800	Spline	550
	1.35	45-180	59.28	54,800	Body	550
	1.35	45-180	59.28	45,900	Body	550
4353 ESR	1.468	20-160	27.3	9,700	Spline	400
M113A1	1.468	20-160	27.3	47,920	Spline	400
	1.468	20-160	27.3	74,100	Spline	400
	1.468	20-160	27.3	49,840	Spline	400
	1.468	20-160	27.3	12,550	Spline	400
	1.468	20-160	27.3	14,460	Spline	400
	1.468	20-160	27.3	52,970	Spline	400

Table 1

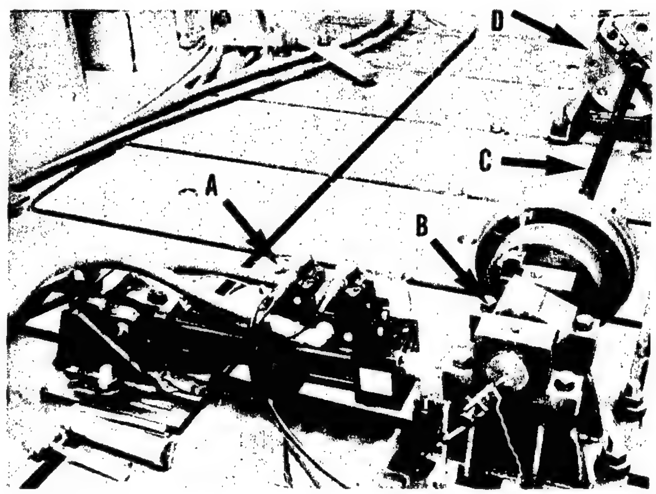


Figure 11

was not considered satisfactory for determination of the torsional endurance properties of the base material. A typical failure is shown in Figure 13. A very small fatigue crack started in the root of the spline, which propagated to a brittle failure of the bar. It was concluded that for new vehicles such as the XM2 the spline size might be increased to prevent spline failures; but for the M113, an increase of spline size would have too great an impact on logistics to be practical.

VAR Steel Considered

Because of the spline failures experienced with the ESR 4353, it was decided the 300M alloy be tested. It is a modified 4340 steel with 1.5 percent silicon specifically developed for aircraft applications requiring high toughness. The aircraft specification calls for a double temper at 575 F after an oil quench. These procedures were followed initially, and a temper at 410 F later was explored without apparent advantage.

Tensile and yield properties were obtained as a function of tempering temperature and are shown in Figure 14; the data compared favorably with that of published data. A torsional stress strain curve for 300M is shown in Figure 15. Two bars were tested and the following data derived:

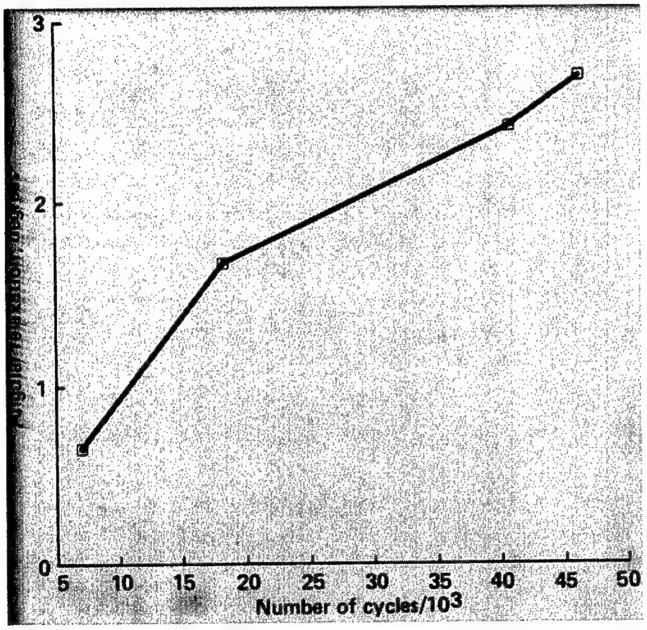


Figure 12

Arrows indicate locations of failure initiation in the roots of adjacent splines at anchor contact line.

Figure 13

	Bar 1	Bar 2
Shear ultimate strength, psi	223,396	227,019
Shear yield strength, psi	163,019	163,019
Angular windup at failure, degrees	159	300
Shear modulus, psi	11.356 x 10^6	11;356 x 10^6

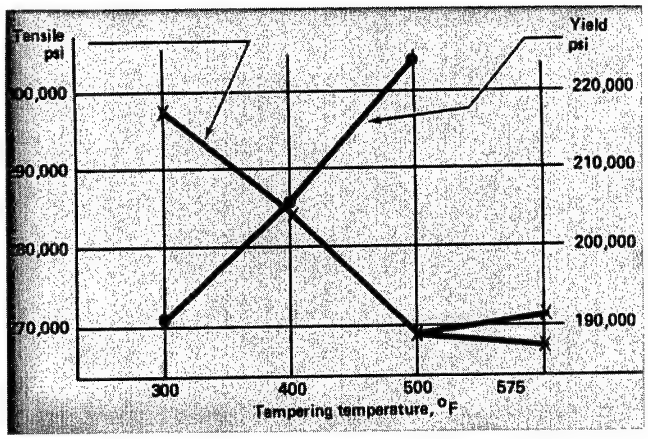


Figure 14

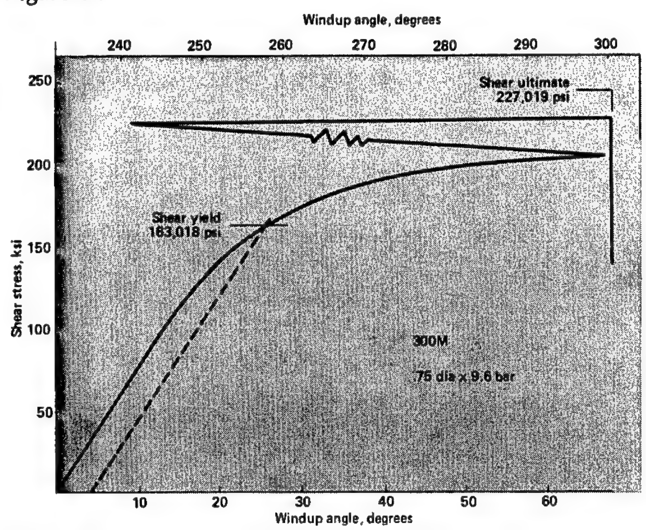


Figure 15

The results are very similar, but the angular windup at failure for Bar 2 was double that for Bar 1. Examination of the bars showed that Bar 1 had twisted over only half its length, and there appeared to be zones of very high plasticity.

XM2 Bars Tested 3500 Miles

The scaled down, half length bars for the XM2 produced satisfactory results. Lowering the minimum stress during the loading cycle had a marked effect, but the bar life was still within the specification. The fact that the failures were essentially all in the body of the bar was encouraging. The decision to test full diameter (1.882 in.) half length bars was made, and these bars again met the requirement, but the preponderance of failures shifted to the spline. With these results, it was decided that the balance of the tests of 300M would be conducted with full sized XM2 bars.

The question of machining or rolling the splines remains open. A majority of the full sized bars had the splines rolled. The average life of the full sized bars was satisfactory. The fracture appearance, which showed extensive crack propagation before ultimate failure (Figure 16), was also satisfactory—very few spline failures were observed. The few machined splines were on bars that failed in the body, but they also were tempered at a lower temperature, so no definite conclusions could be drawn. The bars with rolled splines that were tempered at 575 F were duplicated and put on a vehicle for field test. The bars have operated on an XM2 vehicle for a total of 3500 miles and only one failure has occurred. This result is considered quite satisfactory, conpared with experience from torsion bars subjected to similar duty.

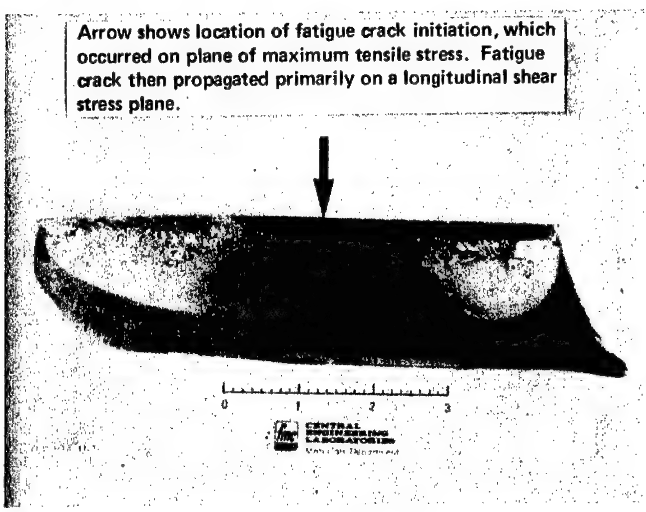


Figure 16

Full Sized Bars OK for M113A1

Full diameter, half length 300M bars demonstrated adequate life in a stress range of 20,000 to 160,000 psi. However, all failures were in the spline. To prevent spline failure at the same maximum shear stress, a full sized bar with a body diameter of 1.405 inches was tested. This bar had an extremely long life of 125,000 cycles, finally failing in the body. Five more full sized bars were tested at TARADCOM with similar results. Subsequent to these tests, it was decided that field tests would be carried out. Two M113A1 vehicles were tested by the Army at Yuma for 6600 and 6200 miles, respectively, without a bar failure.

Austempering Ineffective

To evaluate the effect of austempering, four half length 300M bars were produced. After heat treatment, endurance testing showed their average life was only 28,000 cycles, so it was concluded that austempering offered no advantage over conventional heat treating.

VAR Steel Not Readily Available

Since toughness, in addition to strength, seemed to be the controlling factor for high fatigue life, a new Republic Steel alloy that was reportedly an optimized 300M was investigated. (It is essentially 300M with a higher silicon content—2.4%.) The nominal properties include a tensile strength of 312 ksi, a yield strength of 271 ksi, an area reduction of 30 percent, a Charpy V-notch of 15 foot-pounds, and a fracture toughness of 54.

Two torsion test bars received a cold treatment of -110 F after quenching and a temper of 575 F. Table 2 gives the properties that were obtained on the two bars. The torsion stress strain curve is shown in Figure 17.

	Bar 1	Bar 2
Shear ultimate strength, psi	239,615	242,000
Shear yield strength, psi	193,752	167,719
Angular windup at failure, degree	416	461
Shear modulus, psi	11.538×10^6	10.795×10^6
Hardness, Rockwell C	55-56	55-56

Table 2

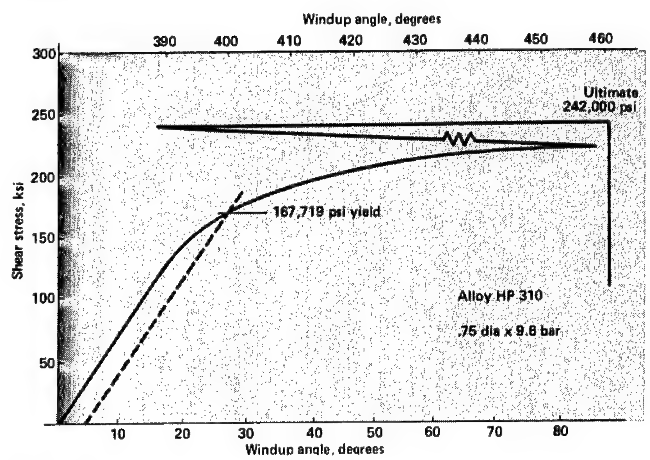


Figure 17

Table 3 gives the mechanical properties obtained from four test bars. The results agree with those published by Republic Steel with the exception of elongation, which was reported to be nominally 10 percent. Temper A was a double temper at 550 F, and temper B was at 410 F. All samples were quenched and cooled to -110 F for 1 to 2 hours.

	Temper A	Temper B
Tensile strength, ksi	299	300
Yield strength, ksi	272	261
Percent elongation, 2 inches	6	6
Hardness, Rockwell C	50	50

Table 3

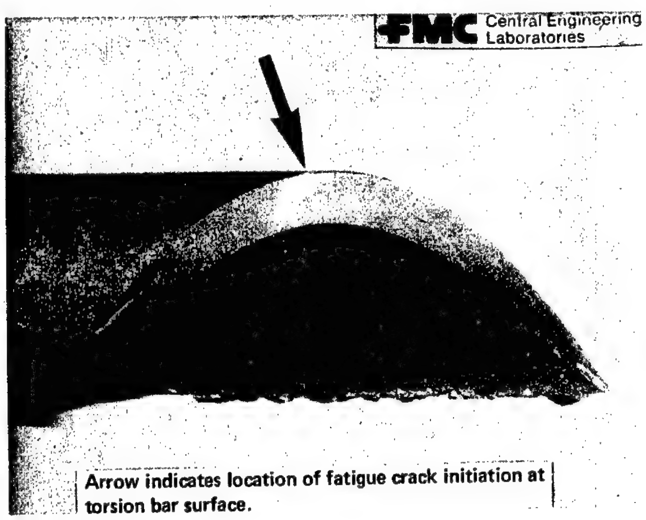
Belgian 4357 ESR Steel Short Lived

A torsion stress strain test was not made on this material, but tensile tests showed a yield strength of 247 ksi, an ultimate strength of 294 ksi, and elongation of 2.3 percent. Half length 1.3 inch diameter bars with the 113 spline were tested and the average fatigue life was low, so no further testing was conducted with this material.

Case Hardened Bars Examined

During the course of this program in which new materials were being investigated, the Forrest Product Division of FMC was testing a new process on M113 size bars made from 4140 and 4150 alloy steel. They were case hardened to a depth of aproximately 20 percent of the diameter. Analysis of these tests revealed that shot peening greatly improved the fatigue life of the torsion bars fabricated from both alloy types.

Fracture surfaces indicated that all of the failures had the primary fatigue crack initiation in the bar body. In all of the crack initiation sites that were observable, initiation occurred at the torsion bar surface. A typical example of the type of fracture surface observed is shown in Figure 18. Case core fatigue crack initiation sites were not observed; however, not all initiation sites were observable, either because the initiation site was not exposed at the location of final failure or because it was mechanically obscured by the final failure of the bar.



Arrow indicates location of fatigue crack initiation at torsion bar surface.

Figure 18

Material Selection Finalized

300M—Torsion bars of this material operating at a shear stress of 180,000 psi have acceptable fatigue performance.

Thermal mechanical processing parameters greatly affect the fatigue performance of torsion bars; therefore, these parameters must be closely controlled to optimize bar performance. The following parameters were optimized with respect to fatigue performance:

- **Spline rolling versus hobbing**—Spline rolling did not increase fatigue life, so the manufacturer should be given the option of either rolling or hobbing the splines.
- **Spline size**—Due to the concentration of stress at the root of the spline teeth, the minor diameter of the spline should be 1.15 times the body diameter.
- **Shot preening conditions**—Overblasting at intensity levels either too high or too low, with insufficient coverage, results in a lowering of fatigue performance. It was found that optimum fatigue life was attained by assuring 100 percent minimum coverage with Almen intensity levels of 0.007 to 0.010 C on the bar body surfaces and 0.012 A in the splines, using hardened shot of Rockwell C50 to C60 hardness. Shot peening at intensities in excess of 0.015 C resulted in shock induced, retransformed subsurface structure which created sites for fatigue crack initiation to occur.
- **Austempering of 300M**—Austempering resulted in a 50 percent reduction of fatigue life when compared with conventional quench and temper.
- **Heat treatment**—Heat treating should be carried out in salt pots with the bars in vertical position, suspended from the top to minimize distortion. The effect of straightening after heat treatment was not evaluated, but it is not recommended because it is difficult to control.

ESR steel is not feasible at the present time, condsidering the cost of raw material.

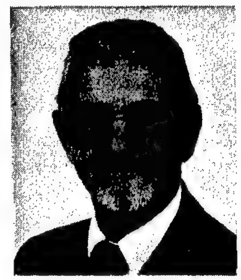
Processing Techniques Recommended

Induction hardening of bars—Optimizing the induction hardening of bars will be pursued because (1) it offers a significant cost savings, (2) it can be used with many of the low cost alloys, and (3) the process uses less energy.

300M alloy—This material should be used for applications requiring an endurance stress of 180,000 psi until the case hardening process is refined.

475 draw for 300M—Investigation of the possible advantage of this material will continue, since tests indicate that this process reduces spline failures.

WILLIAM T. HIGHBERGER is a metallurgist in the Materials and Processing Branch, Engineering Support Management Division, Naval Air Systems Command, Washington, D.C., where he is responsible for titanium applications, metal matrix composites, and manufacturing technology for metals. Prior to this he was an investigator and project engineer in various ordnance programs at the Naval Surface Weapons Center, Dahlgren, Virginia. He graduated from the College of Wooster in 1938 with a B.A. in mathematics and worked in mill metallurgy for Republic Steel Corporation, Massillon, Ohio, from 1940-1953, with time out for naval service in World War II. Mr. Highberger is currently a member of AWS, ASM, and AIME.



Missile, Aircraft Fabrication Revolutionized

NAVAIR Pushes SPF/DB for Structures

Superplastic forming/diffusion bonding (SPF/DB) of titanium material figures prominently in the plans of the U. S. Naval Air Systems Command as it struggles to hold costs down, yet develop a manufacturing capability that remains in the forefront of technology. Side benefits that are fully expected to accompany the arrival of this capability within the NAVAIR umbrella include marked weight savings in structural components, sharp decreases in costs of fabrication, considerably less energy requirements and greater long term reliability of structures; the Naval Air Systems Command is stressing SPF/DB in its current manufacturing technology efforts.

Large Design Flavor

Three principal net shape metal working systems for titanium are being qualified through the manufacturing technology program by the Naval Air Systems Command. These are hot isostatic pressing (HIP) of powder for equiaxed parts, isothermal shape rolling (ISR) for high plan aspect ratio parts, and superplastic forming/diffusion bonding (SPF/DB) for large plan areas. The first two are mainly concerned with making existing parts more cheaply, while SPF/DB with a large design flavor has potential for revolutionizing aircraft and missile fabrication when all the design possibilities are exploited.

The means for such an unconventional fabrication is provided by the propensity for use of medium strength titanium alloys such as Ti-6A1-4V by aircraft manufacturers to superplastically form (with up to 1000% elongations) and concurrently diffusion bond in the same temperature range—somewhat below the transformation temperature.

Titanium Alloys Most Suitable

Basically, superplastic forming requires a fine grained material with a relatively low strain rate. Multiphase alloys are usually required to inhibit grain growth and encourage grain boundary sliding, which is thought to be the dominant mechanism for superplasticity. Although

certain steel and aluminum alloys have exhibited superplastic behavior, the titanium allous provide by far the greatest opportunities for several reasons, the principal one of which is the capacity for self diffusion bonding at superplastic forming temperatures. Fine grain size is easily obtained with the common titanium alloys by thermomechanical means. Yttrium additions also have been shown to enhance grain refinement in titanium and promise to further promote superplastic behavior. Finally, titanium alloys provide the best strength to weight properties and require little or no maintenance.

With only slight redesign, existing titanium assemblies made of builtup parts can be fabricated by SPF/DB at greater than 50% cost saving; also with considerable weight savings through elimination of mechanical joints. So efficient is this system that savings in both cost and weight can be made even when substituting for aluminum, as will be shown later for an F-14 part.

Technique Self Inspecting

In the SPF/DB process a part typically is made by placing a cleansed titanium alloy sheet in a closed die system and introducing argon gas at 200 to 300 psi and 1600-1750 F temperature. The workpiece is expanded into a female die detail. The sketch in Figure 1 illustrates the several possible schemes which would typify one, two, three, and four sheet geometries.

Where diffusion bonding is part of the process, the area not to be bonded is coated with "stop off" to create an intentional disbond when expansion takes place (Figure 2). The diffusion bonds are self inspecting, since poor bonding would become separated under expansion loading. A checkerboard pattern then can be used to make the "double sine wave" or "bubble core" sandwich. Diffusion bonding may be used to both create sandwich patterns and to add bosses, attachment lugs, or other details.

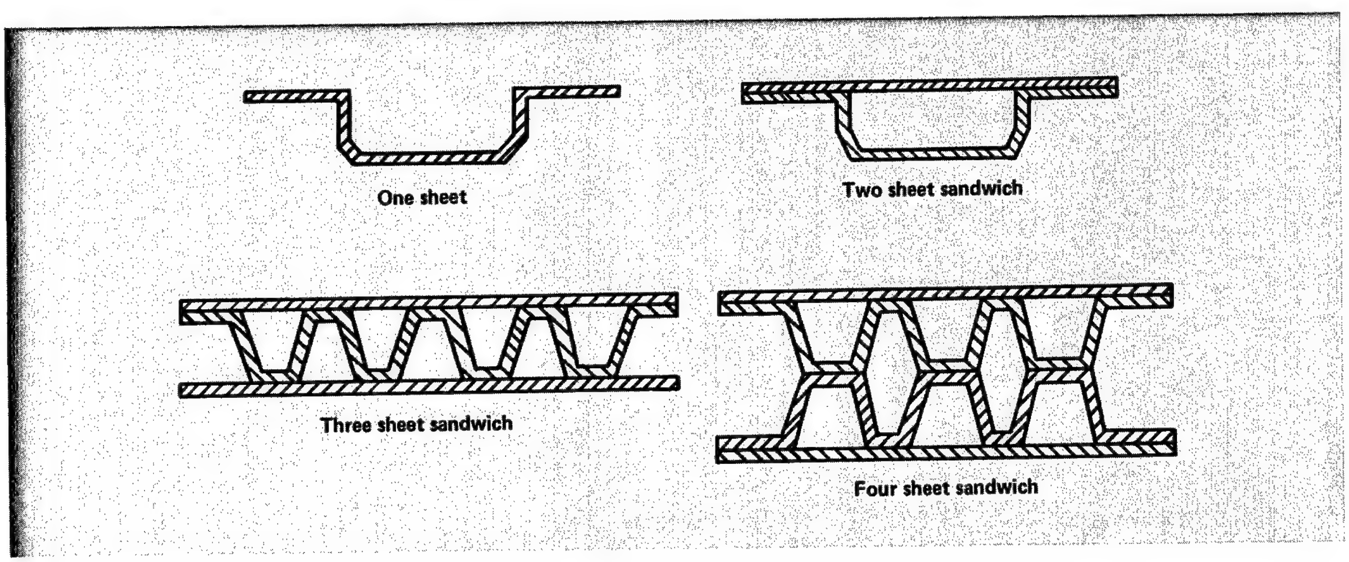


Figure 1

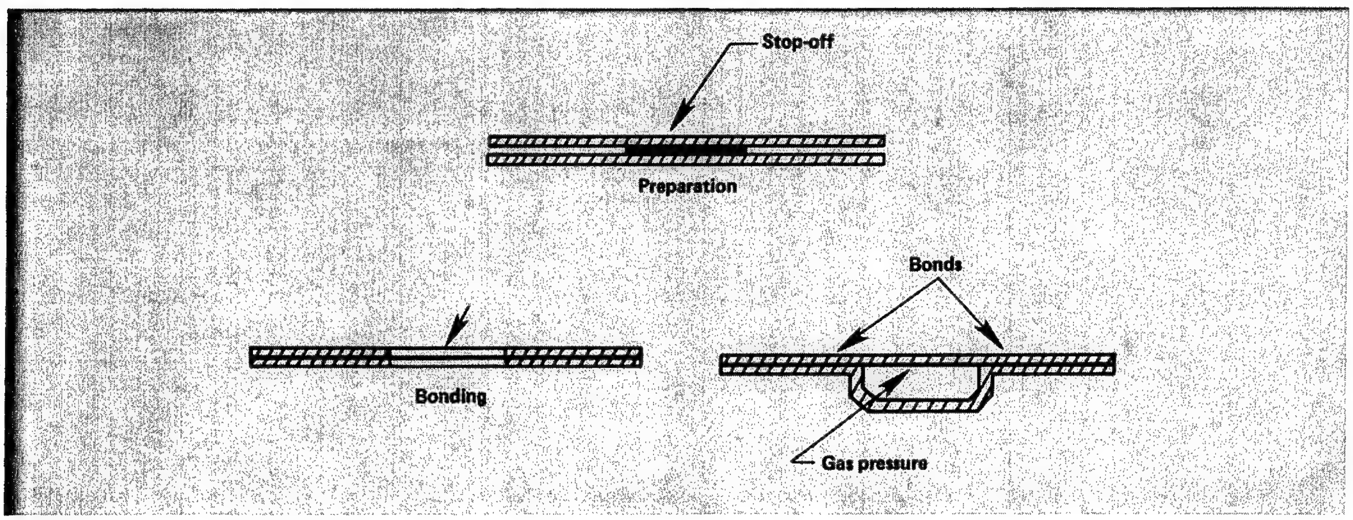


Figure 2

Selective reinforcement with ceramic fibers would add a new dimension in future configurations.

New Navy Alloy Super Strong

The plans at NAVAIR for SPF/DB involve four projects. The first project, funded by the Air Force, is to demonstrate an ultrahigh strength SPF/DB titanium sandwich construction using the new Navy titanium alloy, CORONA-5, at 160 ksi tensile strength. The use of such a high strength, high toughness alloy would permit even greater weight saving.

The next project is to make a glove vane for the F-14. This part, shown in Figure 3, is a 3 inch deep, 7 foot long, 3 foot wide triangular aluminum alloy (2024) structure consisting of 64 parts held together by 1700 fasteners. When the part is made of titanium sandwich construction, a saving of 10% in weight and 25% in cost is projected. While this is a very substantial benefit considering that titanium is 5 to 8 times higher in price than aluminum, the greatest saving yet may be in reduced maintenance costs—the titanium version requires little or no attention for long periods of time.

New Design Tool Provided

The third project will be accomplished as part of the Air Force program "Limits of the Process". The objective is to construct bubble core sandwich panels of graduated weights and corresponding mechanical strengths. This information, included in a design manual, will allow designers to select their weight parameters without requiring an empirical test program for each design.

More Expensive Material Less Costly

Last, an overlooked area is that of an application in missile technology. In a planned program for the Supersonic Tactical Missile (STM) developed by Vought Corporation, an innovative example of SPF/DB called "Expanded Tube Technology" is being explored. This technique exploits superplasticity of titanium for cylindrical shapes in which a welded tube is expanded into a female cylin-

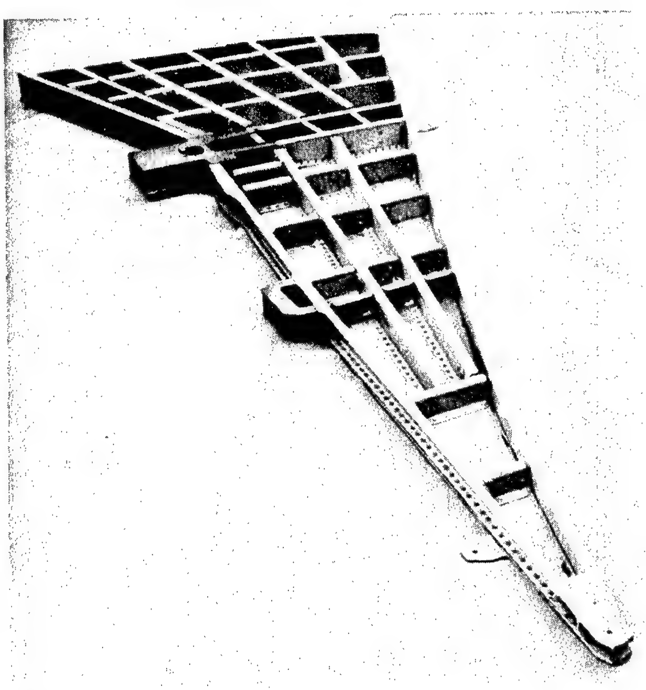


Figure 3

Figure 4

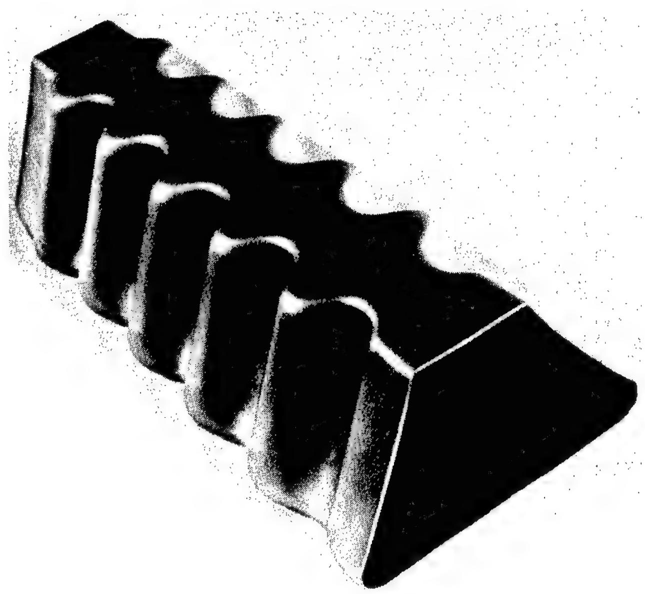


Figure 5

drical die to form various detailed shapes. Figure 4 shows a part which demonstrates the potential of the process— the starting diameter is at the end next to the inlet tube. A part made from a triangular preform exhibiting sine wave geometry is shown in Figure 5. So efficient is the process that again, as in the case of the F-14 glove vane, titanium can be substituted for a cheaper metal (in this case, 17-4pH steel) yet save greater than 50% of the cost. This technique promises to pave the way for a new generation of low cost missiles characterized by unlimited shelf life.

The Naval Air Systems Command definitely has a deep commitment to superplastic forming/diffusion bonding of titanium for fabricating aircraft and missile structures for

- Weight saving
- Cost saving
- Energy saving (through net shape technology)

and, most exciting of all, to provide **maintenance free systems.**

Savings Up To 75%

Precision Parts Pressed From Scrap

Production of high strength, high density precision parts from scrap in a single step operation may not quite be making the proverbial silk purse from a sow's ear, but it's a concept that should interest a lot of manufacturers, nonetheless. Particularly if they can reduce costs by 15 to 75 percent over conventionally produced parts.

Well, this is exactly what a process recently developed at IIT Research Institute offers. It uses scrap from virtually any metal—IITRI has worked primarily with aluminum to date—to produce either precision net shape parts of preforms for forging or extruding. It doesn't require expensive equipment, costs are low, and the product is improved in many ways over conventional powder metallurgy or cast and wrought products.

Called hot pressing, or particulate metallurgy, the process takes scrap metal and inexpensively converts it into free flowing particles that will uniformly fill a die. These particles are heated to the same temperature as a lubricated die cavity, then hot pressed to net shape and close tolerance. The process can use existing commercial equipment and will yield high production rates (pressing requires two seconds or less and multiple dies can be used).

Better Parts . . .

The resulting parts have nearly uniform mechanical properties in all directions—properties that are superior to those of parts made by any other known process except extrusion or forging. And in those cases, the properties are equal. In addition, the parts are virtually 100 percent dense—essentially leakproof. Precise dimensions and close tolerances are easily obtained and the microstructures of preforms are superior to those of conventional cast and wrought iarts.

And Lower Costs

The major advantage, however, lies in the economics of the process. Precision parts are peoduced at a very low unit cost when compared with other processes. Costing analysis has shown that equivalent parts made by die casting can be undersold by 15 percent, powder metallurgy parts by 25 to 50 percent, and forgings or machined bar stock by 50 to 75 percent.

The process could be adapted to a wide variety of parts. Net shape parts might include automobile components, connecting rods, gears—virtually any small part

SAMUEL STORCHHEIM received B.S. and M.S. degrees in Metallurgical Engineering from the Polytechnic Institute of Brooklyn. He has over 20 years of experience in powder metallurgy including the pioneering of direct rolling of heated metallic particles into finished strip, aluminum powder metallurgy using protective sintering atmospheres, and aluminum powder metallurgy sintering in air. He currently is working at IIT Research Institute developing the use of squeeze casting technology and the new hot pressing method. Mr. Storchheim has over 30 patents and 70 publications.

that will fit into such things as appliances, automobiles, and business machines. IITRI is now working with a number of companies towards developing process parameters for specific parts. The appliance industry, for example, is taking a particularly hard look at hot pressing applications.

From Aluminum Scraps . . .

Just how does this revolutionary process work? Working with aluminum, IITRI procures EC (electric conductor) scrap clippings such as those shown in Figure 1. These clippings are basically over 99.5 percent pure. (There is a tramp pickup of about 3 percent copper, however.) Alloys such as 7075 and 2014, including machine shop turnings and borings, can also be used.

As the process was originally developed, the aluminum scrap is melted in air and poured into a rotating perforated cup. Molten metal is forced through openings in the cup and uniform pieces are snapped off the emerging streams of liquid metal. These needle shaped particles are about ¼ inch long and 0.010 inch in diameter. They are free flowing at either room temperature or elevated temperatures, in contrast with conventional atomized aluminum powders. This free flow is the key to the process.

With subsequent development, the melting step has been sidestepped in most cases. The scrap itself can now be hot pressed after a minimum of pretreatment—This development has further improved the process. The needle like particles tended to flow laterally and sometimes to back extrude, producing forged like structures. This is not a problem with the latest development, and parts can now be made in simple, inexpensive dies. A top punch, bottom punch, and die body is all that is needed.

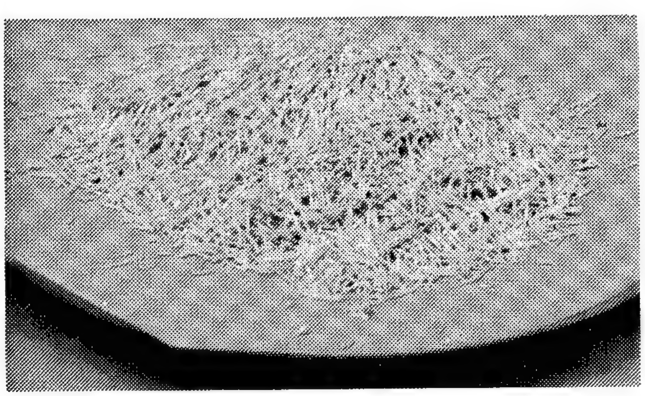


Figure 1

To Parts Or Preforms

The basic setup for pressing is shown in Figure 2. A very important element in the process is proper die lubrication. The die cavity is sprayed with graphite immediately before the scrap material is fed in so there is fresh lubricant on the die walls for each compaction. The cavity is then filled from the feedbox. As the feedbox retracts from this filling step, it uniformly levels the material in the die cavity. The top and bottom punches are closed and the combination of pressure and heat consolidates and welds the particles to form a compact or net shape part. (The feasibility of using a single action press has been demonstrated, but double action operation appears preferable in regard to die wear, lubrication, and properties of the part.) Using this process, IITRI is able to form acceptable parts from aluminum scrap needles in 0 to 2 seconds at a temperature of 950 F and pressure of 12 tsi.

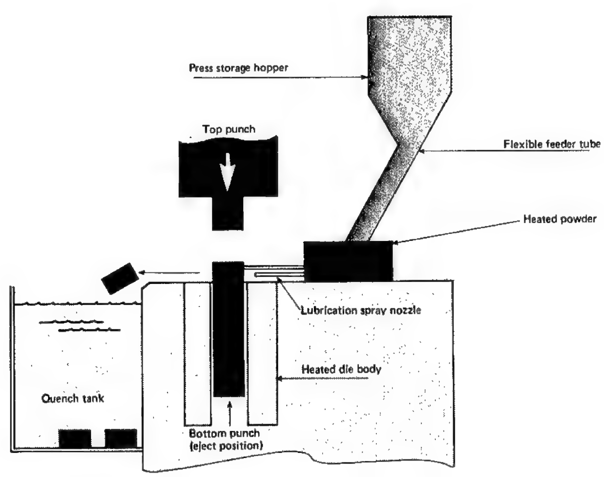


Figure 2

Figure 3 shows a typical hot pressed slug made from aluminum particles. This slug appears to be quite simple. However, it demonstrates another advantage of hot pressing as compared with conventional powder metallurgy. With both a diameter and thickness of two inches, this compact could not be produced by conventional powder metallurgy methods. Full compaction could be obtained only by mixing organic lubricant waxes with the aluminum powder. Normal sintering methods would not remove all the wax from the center of the compact and it would be unusable. Using unwaxed powder, maximum compact thickness for a powder metallurgy part would be about ½ inch. Larger parts would gall and seize. Using the proprietary lubrication approach in IITRI's process, the only apparent limit to the thickness of a hot pressed part is that imposed by the press and the die.

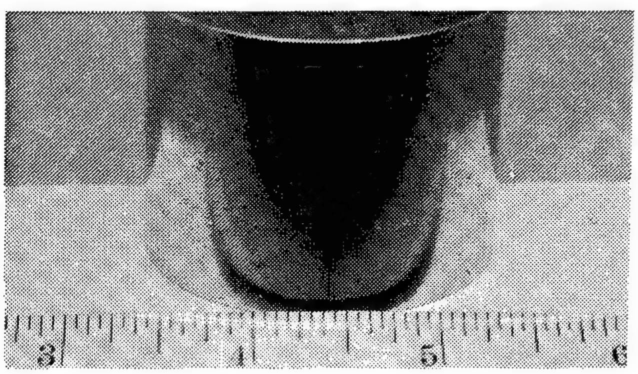


Figure 3

Further Processing Simplified

After pressing, the top punch is retracted and the part is ejected by the bottom punch. When the feedbox moves forward to refill the cavity (which is again lubricated), the compact, still at 950 F, is pushed into a water quench tank. Thus, it is quenched from the solution annealed condition and naturally age hardened at room temperature, reaching the T4 condition at virtually no extra cost. The quenching also improves tolerance control (to better than ±0.0005 inch per inch) and limits oxidation, producing better properties and a superior surface.

Another advantage is that parts coming out of the die have a uniform coating of graphite lubricant, which has been transferred from the die. Thus, the normal black coating applied to preforms for rapid heat transfer when furnace heating prior to forging is not needed. For precision parts pressed to net shape, the lubricant coating is easily removed in a low cost vibratory cleaning operation. This operation also deburrs the part, giving it a frosty finish.

Improved Properties

The hot pressed preforms have substantially better microstructure than the cast and wrought parts. They show fine, equiaxed grains throughout with minimal distortion, in contrast to the wide range of grain sizes and heavy deformation in cast and wrought parts.

The parts also have isotropic properties, whereas cast and wrought parts have definite directional properties. With the latter, the critical limiting factor in design has been the short transverse direction, which has the lowest mechanical properties. This need no longer be a problem. In hot pressed parts, ultimate tensile strength shows no more than 5 percent variation in the three directions, and elongation is nearly as uniform.

As noted, density of the parts is virtually 100 percent. As a result, they are leakproof to a minimum of 2500 psi hydraulic oil pressure and 400 psi helium gas pressure. Parts can be used as formed in a variety of fluid flow applications.

Wrought Like Properties

Properties are like those of wrought type products, such as forgings. This is because the hot pressing stress-strains the part extremely rapidly, leaving no time for recrystallization and grain growth. The parts are at an elevated temperature when they are plastic and flow easily under pressure. Consequently, they level out very uniformly (within 0.001 inch or less on thickness) and move easily into such spaces as gear teeth and splines. As a matter of fact, very precise dimensions and tolerances seem practically inherent to hot pressed parts. This is

because the components easily take on the dimensions and geometry of the die; the better the die, the better the parts. This sort of behavior is very different from conventional powder metallurgy.

Particulate metallurgy parts respond as if cold worked, so that they attain very high mechanical properties (Table 1). Strengthening is also a function of the relationship of surface area to volume for the particles used. The lower that value, the greater strengths. Apparently, the greater the volume of material to be worked, the more cold working can be induced into the particulate, imparting greater strength and hardness.

In addition to improved microstructure and excellent mechanical properties, hot pressed aluminum parts can be welded and will take any conventional aluminum finish—mechanical, chemical, or electromechanical.

Cost Savings and More

The significant savings mentioned earlier can be attributed to a reduction in raw material cost of about 50 percent, to the short dwell time of the press, and to the fact that the process is essentially a single stage operation. Additionally, capital investment and overhead costs are much lower, less energy is required, and the process is practically pollution free.

As noted, multiple die cavities can be used to increase productivity. Multiple dies appear justifiable for annual production quantities of around 100,000 units. Figure 4 shows results of a cost analysis of parts on the basis of increased production rates. From these curves, the minimum number of parts per hour needed to give a desirable low cost (usually right after the knee of the curve) is obtained. The figure also shows the number of

Typical Mechanical Properties of Hot Pressed Aluminum Parts[1]

Material	Density, %Theoretical	UTS, psi (MPa)	Elongation, %	Hardness, R_h	Surface Area/ Volume x 10^{-1} in.
1100 Al needles	>99	14 600 (103)	—	70.3	500
1100 Al cold rolled 40%	~100	19 900 (138)	—	88.7	
1100 Al 100 mesh powder	>99	13 585 (97)	31.8	44.5	1500
Scrap Al + 3% Cu	~100	22 700 (159)	2.4	97.6	180
Scrap Al + 3% Cu	~100	21 875 (152)	4.2	84.2	415
Scrap Al + 3% Cu	~100	18 995 (131)	5.0	90.7	760
7075 Al swarf	>99	52 665 (365)	—	97[2]	200
Mg ribbon[3]	>99	27 200 (186)	5.2	28	360
Iron carbonyl[4] powder	>99	96 200 (662)	2	12[5]	50 000

1. Air cooled from 950 F (510 C) / 12 tsi (165 MPa) / 2 s; 2. Rockwell E scale; 3. 950 F (510 C) / 24 tsi (7 kPa) / 2 s; 4. 950 F (510 C) / 50 tsi (690 MPa); 5. Rockwell C scale.

Table 1

Editor's note: The Editorial staff is saddened to report that, since writing this article for the Army ManTech Journal, Mr. Storchheim has expired. Succeeding him as Manager of Particulate Research and Development at IITRI is Mr. S. Rajagopal, who is carrying on several projects that Mr. Storchheim instituted. Inquiries may be addressed to Mr. Rajagopal at IIT Research Institute, Metalworking and Foundry Technology, 10 W. 35th St., Chicago, Illinois 60616.

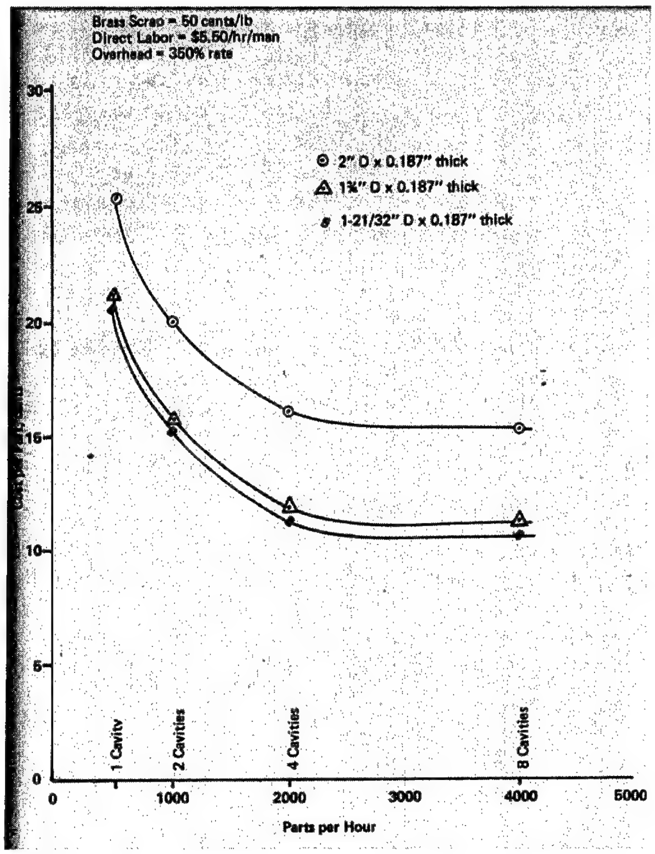


Figure 4

die cavities required. In the curves shown, it turns out that the best way to proceed would be with four cavities at 2000 parts/hour. Going to eight cavities does not reduce costs significantly but does raise die charges as well as increase the difficulties of manufacture.

These difficulties arise because of the virtually 100 percent density of the parts. Pressure compensation for overfill per die cavity must be considered. Any overfill could cause punch breakage by overloading the punch during pressing. Thus, a hydraulic equalizing arrangement is required for multiple die cavity production. When it can be tolerated, a lesser part density requirement of 95 to 98 percent could eliminate the need for the equalizer.

Process Versatile

Work with the process has not been limited to aluminum. Table 2 shows property data for some of the other metals that have been hot pressed at IITRI. Quite positive results have been obtained with magnesium, iron, and copper. The ultimate tensile strength obtained for magnesium is like that of annealed wrought stock i.e., about twice that of cast pure magnesium. With iron, the ultimate tensile strength equals that of heavily cold worked sheet.

Nor is the process limited to scrap metals, though that is where the greatest savings lie. Primarily metal also can be used and the process will remain highly competitive with other metalworking methods.

	Density, % of Theoretical	UTS, psi	Elongation, %	Rockwell Hardness, H scale	SA/Vol x 10^{-1} in.
1100 Al, needles	>99	14,600	–	70.3	500
Same, cold rolled 40%	100	19,000	–	88.7	
1100 Al – 100 mesh powder	>99	13,585	31.8	44.5	1,500
Scrap Al + 3% Cu	100	22,770	2.4	97.6	180
Scrap Al + 3% Cu	100	21,875	4.2	84.2	415
Scrap Al + 3% Cu	100	18,995	5.0	90.7	760
7075 Swarf	>99	52,655	–	97 R/E	200
Mg Ribbon 950 F/24 tsi/2 sec	>99	27,200	5.2	28 R/H	360
Iron Carbonyl Powder 950 F/tsi/2 sec (10 micron diameter)	>99	96,200	2	12 R/C	50,000

Table 2

Facility,
Design Developed
Fiberglass Rotor Produced

PAUL S. BAUMGARDNER is Chief, Manufacturing Technology, at Bell Helicopter Textron, where he is responsible for all manufacturing development activities. Before joining Bell in 1974, he was Chief Manufacturing Engineer at Lockheed's Murdock Machine & Engineering Division for three years. Major programs included Lockheed L-1011 slats and pylon and McDonnel-Douglas F-15 stabilizer fabrication. At Solar from 1968—72, he served as Program Manager on the Minuteman III Titanium Shroud Program, Manned Orbiting Laboratory Electronic Cold Plate Program, and AEC Hot Formed Titanium Shell Program. During an eleven year stint at General Dynamics, Solar, and LTV Aerospace, he acquired experience on programs involving the B-58, F-4, A-7A, F-111, and C-5A. He is a member of the American Helicopter Society and Society of Aerospace Materials and Process Engineers.

Photograph

Unavailable

In a two pronged development effort, Bell Helicopter Textron has designed the first American made fiberglass rotor blade to be certified by the FAA and at the same time laid out production facilities for the blade. The 33 inch cord blade designed for the 50 foot diameter rotor of the Model 214 transport will be the largest fiberglass blade ever flown on a helicopter. Figure 1 shows the first test flight of a Model 214 fiberglass blade in 1975.

Fiberglass blades offer several important advantages over conventional metal blades:

- Higher fatigue strength
- Insensitivity to small defects
- Gradual failure modes
- Freedom from corrosion
- Damage tolerance
- Ease of repair.

Longer Life, Greater Safety

These factors will result in significantly lower life cycle costs. Bell predicts the blades will last two and one half times longer than present 214 blades as well as increase operational safety.

Because of these advantages, Bell made a major commitment to the development of fiberglass main rotor blades more than five years ago. Several company funded programs have followed, culminating in the FAA certification of the 214 blade in July of 1978.

Initial FAA approval is for a retirement life of 2,400 hours. However, Bell is confident that a retirement life in excess of 10,000 hours will be achieved when in-plant and service testing are completed.

Production Set for Early 1980

Commercial helicopter operators very soon will begin to realize the benefits of this technological advance. The

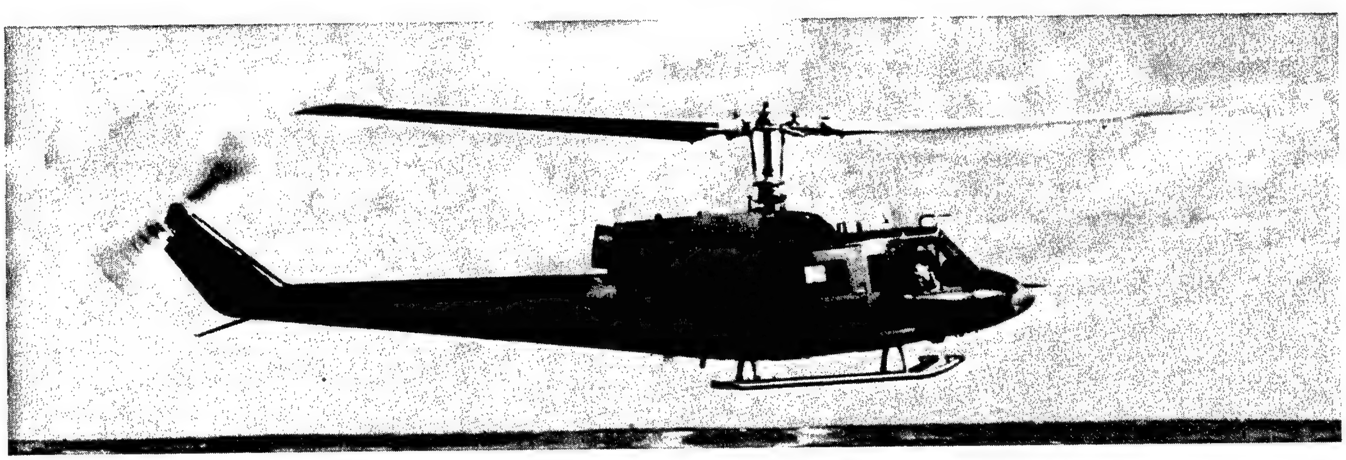


Figure 1

fiberglass blades will initially be available as replacements on operational 214B's. They will then become standard equipment on production 214's, eventually encompassing the entire series. A derivative of the blade will be designed and manufactured for the new twin engine 214ST.

Service testing of the fiberglass blades, lasting as long as 1,200 hours or one year, is under way. The blades will be closely monitored for types of usage and environmental and mission condition. After service tests, they will undergo engineering evaluation, including stiffness and wear checks. Then some of them will be cut apart for test coupons to check material properties.

Bell believes that the program results—basic design, materials selection, and acquisition of unique manufacturing equipment—will contribute significantly to making fiberglass blades economical and practical.

Prepreg Roving for Spars

With introduction of this blade, Bell is the only manufacturer using preimpregnated fiberglass roving for spars. The prepreg roving is less expensive than tape and is more adaptable to machine fabrication methods. This will enable the company to maintain better quality control during production of the large blades than with hand layup methods.

Volume Production Capability A Goal

Manufacturing methods were developed along with the blade design and construction, since volume production capability was a major goal of the program. The blade, shown in Figures 2 and 3, has a spar comprised entirely of machine made elements; two types of filament winding machines are used to make the spar details.

An orbital machine winds the spar caps, which are made of spanwise oriented S_2 glass fibers that carry bending loads and centrifugal force. The fibers of these spar caps wrap around the sleeve of the attachment bolt to the hub, forming integral attachment lugs to the hub. Torsional loads in the spar are carried by layers of filament wound cross ply material tubes located inside and outside the spanwise spar caps. These tubes and the trailing edge are wound on the second machine.

The blade skins consist of layers of nonwoven, cross ply E-glass. A layer of woven cloth is applied to the outside of the skin to minimize foreign object damage. The skins are supported by a nonmetallic Nomex honeycomb core.

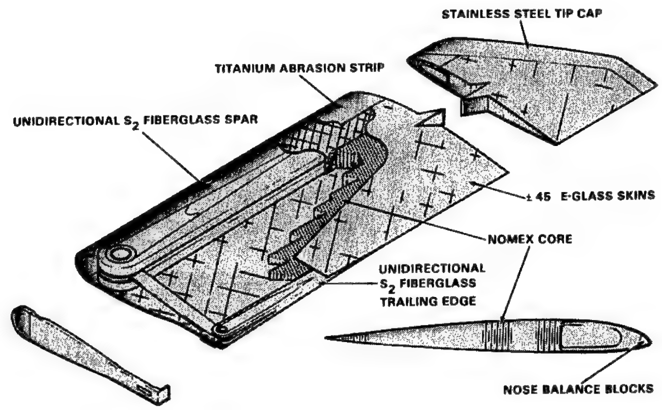


Figure 2

Fiberglass Skins Tougher

Tests have shown that these fiberglass skins and the Nomex core resist damage better than metal blade skins of equal thickness. These skins do not dent as easily; a fatigue crack usually will not grow from a small hole or puncture; and the skin can be patched with less risk of subsequent cracking.

The leading edge of the blade is protected with a full length titanium abrasion strip. The blade is designed so that this abrasion strip and the tip cap can be replaced. Also the paint system incorporates a semiconductive graphite layer to aid in the dissipation of static electricity.

Blade Performs Well

In the event of a lightning strike, the conductive layer causes lightning to flash over the skin to the leading edge, from where it is safely conducted to the hub. Blades tested by the Lightning and Transient Research Institute in St. Paul were not damaged structurally by lightning strikes of 200,000 amperes, which is equivalent to the highest strikes recorded on aircraft.

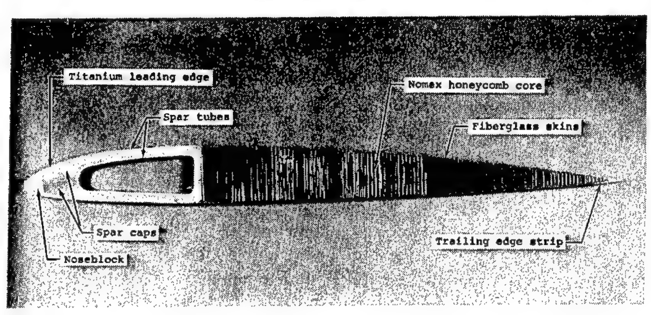


Figure 3

The 214 fiberglass rotor blade also acquitted itself extremely well in ballistic testing. It passed this test by virtually "swallowing" a 23 millimeter high explosive impact round rather than permitting it to exit. Bell engineers attribute this primarily to the tight wraps of the filament wound spar.

The fiberglass blades are the same size as Model 214 metal blades, have a similar aerodynamic shape, and are interchangeable with that blade.

Filament Winding Utilized

The challenge of designing and installing a production facility to manufacture the new blade economically and efficiently tested the ingenuity and creativity of Bell's Manufacturing Development and Equipment Engineering Groups. Close coordination with design engineers was a must.

In many instances, available tools and machines had to be modified. Other equipment was completely designed by Bell and manufactured outside to exacting specifications. In some cases, Bell built its own unique tools. Whatever it took, equipment is now in place for production of the fiberglass blades.

A basic premise for achieving low cost production was to design the major blade components for filament winding. In production, the upper and lower spar caps, the trailing edges, and the inner and outer torque tubes will be filament wound. These components account for 58 percent of the total blade weight.

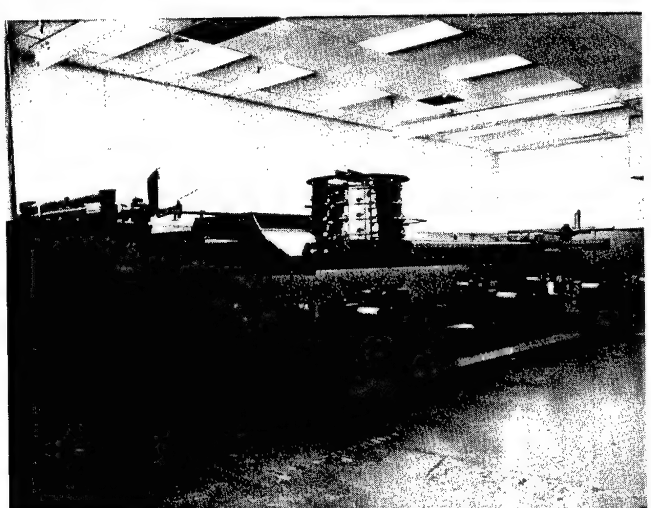


Figure 4

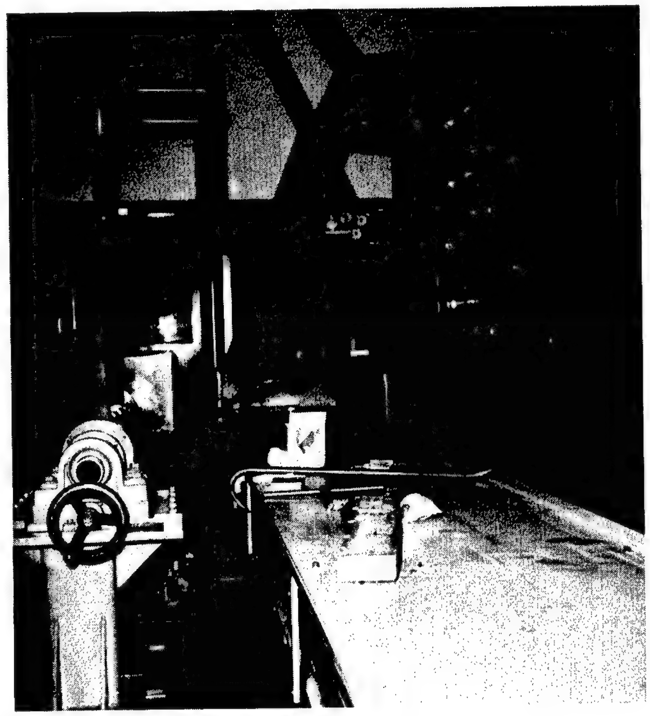


Figure 5

Equipment for Specific Needs

Spar caps are wound on an **orbital pin winding machine (Figure 4)** manufactured to Bell design by Goldsworthy Engineering, Inc., of Torrance, California. This one of a kind machine replaces a conventional filament winding machine Bell had adapted to accept prepreg roving. Bell engineers designed an orbital winding accessory for this machine, enabling it to form spar straps. This prototype orbital winding unit was in service for more than two years without significant downtime.

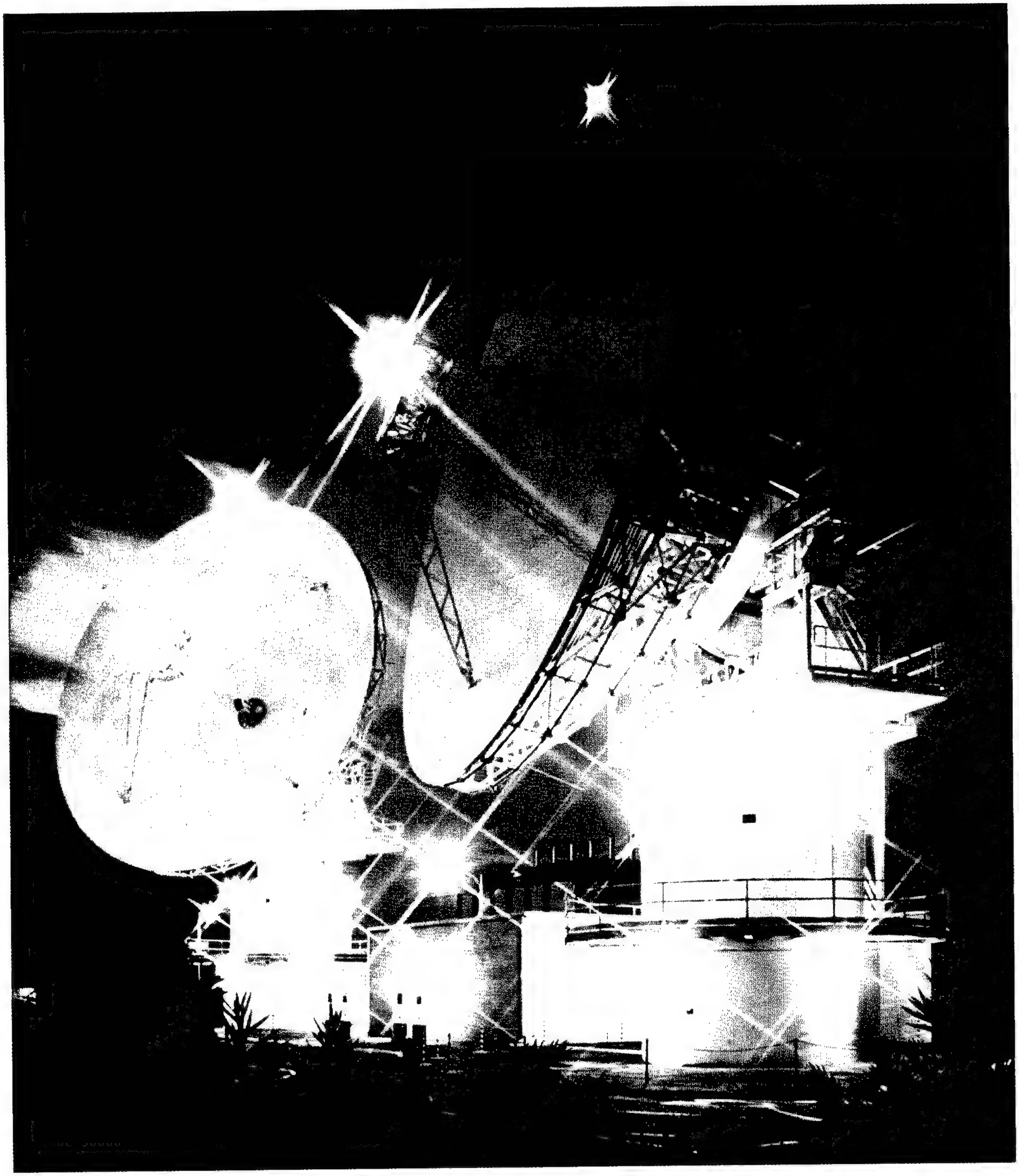
The new production machine is digitally controlled and panel programmed, requiring no software. Every function is controlled by setting a series of thumbwheels. It is capable of high volume production of blades for any model that requires longitudinal structural elements of unidirectional fiberglass. The machine can lay approximately ninety pounds of fiberglass per hour, running sixteen strands of fifty end count prepreg roving. A unique feature is that another head can be added to nearly double production.

For fabrication of the torque tubes and trailing edge, a **filament winding machine (Figure 5)** was manufactured to Bell specifications by McClean-Anderson of Milwaukee. This digitally controlled four axis machine maintains an exact wind angle over a varying shape mandrel. It also can give a torque tube a full 45-degree wrap in one direction, then reverse the wrap for the next layer. It is used to wind

US Army
ManTech Journal

Electronics Plays Vital Role

Volume 4/Number 2/1979



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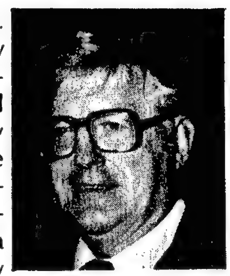
ABOUT THE COVER:

High Capacity Satellite Communication Terminal AN/FSC-78(V) scintillates in the dark in this star filter photograph. With a proven mission availability of 99.9% resulting from experience gained on 23 such installations, this remarkable development of the U. S. Army Satellite Communications Agency, Ft. Monmouth, N. J., will support the National Command Authority, the tri-services, and other DOD agencies in their worldwide communications missions through the remainder of this century.

Comments by the Editor


DR. JOHN J. BURKE

Of all the areas of manufacturing technology that the U. S. Army is concerned with in its push to improve our military production base capability, there is no doubt that the area of electronics has impacted more profoundly on our personal lives and style of living than any other. The many manufacturing technology projects underwritten by the electronics commands through the years have literally established whole new industries that have continued to supply the commercial market after meeting military production base requirements, making possible the production of a myriad of electronics items that have revolutionized our quality of life.

And this is only the beginning, as the work that is going on right at this moment in the laboratories at Ft. Monmouth, Harry Diamond Laboratories, Dover, Huntsville, and hundreds of contractors all over the country is producing the capability to make electronics devices that again will dramatically alter our style of living.

Little credit sometimes has been given the Army electronics organizations and personnel who have been responsible for planting these seeds of production capability in our land, and we hope that this issue of the Army ManTech Journal will serve to make many of our readers more aware of the outstanding achievements that have characterized the various electronics projects emanating from these Army directed laboratories. We long have admired the tenacity with which the staffs of the electronics commands have continued to pursue their short range objectives and long range goals, despite any and all difficulties encountered along the way.

Among the unusual number of articles in this issue of the ManTech Journal we believe our readers will find an interesting and informative mix concerning some significant new achievements in Army electronics. It would be impossible to single out any one as the most outstanding development, as several hold immense promise for our production capability.

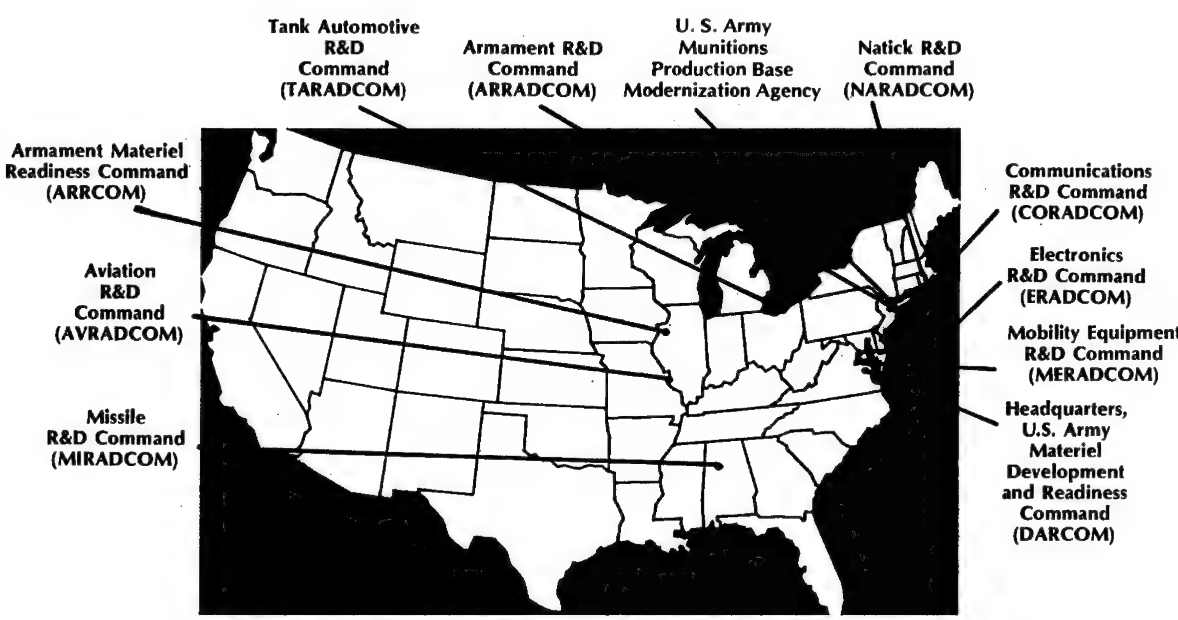
One thread of similarity can be seen crystal clear after perusing the contents of these articles on electronics in the Army—that is the fact that the electronics commands are demonstrating in real terms what our entire MM&T effort in the Army is all about: development of production capability in the event of a rapid mobilization requirement. The titles of these articles tell a quiet story of bringing high unit costs down dramatically as the various electronics devices move out from the laboratory into a production environment, meanwhile maintaining the extremely high specifications required for military use.

The automation of analog systems testing; batch processing of surface acoustic wave devices; oscillator production rates "zooming"; quantity production of quartz crystal units; production rates of hybrid silicon detectors; infrared monitoring of drill wear; laser scan inspection of PC boards—these all imply one thing. Our manufacturing technology projects are paying off more than ever before and we can expect to see even more pronounced benefits derived as we move into a period of "recycling" of previously acquired manufacturing expertise.

Our next issue of the Army ManTech Journal will contain several excellent articles demonstrating this concept of 'recycled' benefits, as they pinpoint validated cost savings experienced because of a previous manufacturing technology program. We believe this method of accountability will serve to further justify many of our current MM&T projects and will build even greater confidence into the Army MT program.

An article of particularly wide reader interest also is carried in this issue of the Journal—an early report on the new trends developing within the Army aviation MT effort as indicated at the Aviation ManTech II Conference held in Corpus Christi the week of February 18. Some significant trends may be developing in airframe fabrication as the results of that conference are implemented.

DARCOM Commands Actively Implementing New Manufacturing Technology Methods



Basic Processes Face Change

Need For MM&T Continues

MARTIN IDES is Chief of the Readiness Programs Division, Logistics Engineering Directorate, U. S. Army Communications and Electronics Materiel Readiness Command, Fort Monmouth, N.J. He is responsible for command management and direction of the Industrial Preparedness and MMT Programs, the Army Procurement Appropriations Program, and the Army Materiel Plan. Prior to this, he was Chief of the Production Division, Procurement and Production Directorate, of the former Electronics Command. He began his career as an electronics engineer in the Research and Development Laboratories after having served during the Korean Conflict in the Army Signal Corps under the Scientific Professional Program. He has progressed through various positions, essentially concerned with the management of major tactical radio programs. He received a Bachelor of Electrical Engineering Degree from Clarkson College of Technology and did graduate work in electrical engineering at Rutgers University. He is a licensed professional engineer and is a member of the National Society of Professional Engineers, the Institute of Electrical and Electronics Engineers, the Armed Forces Communications and Electronics Association, and the American Defense Preparedness Association.

There is probably no other technological area that has advanced as rapidly in recent years as has electronics technology. In a relatively short period of time, we have progressed from transistors to integrated circuits, to large scale integration, to minicomputers and microprocessors, and at the same time have achieved significant advances in night vision and fiber optic technology. Manufacturing Methods and Technology (MM&T) therefore becomes even more significant as a result of these rapid advances.

Editor's Note: Associated with the three major electronic commands at Ft. Monmouth is a subordinate arm of the U. S. Army Aviation R&D Command (AVRADCOM)—the Army Avionics Research and Development Activity (AVRADA). This activity conducts that portion of AVRADCOM's mission pertaining to avionics. This responsibility includes the R&D, value engineering, production engineering, maintenance engineering, product assurance, and human factors engineering for all aviation electronic subsystem and interfaces, air and ground. These encompass air traffic regulation systems, airborne communications integration, navigation, landing systems, environment sensors, aircraft instrumentation, and control mechanisms of the aircraft, in addition to total aviation electronic system engineering and design for all Army aircraft. AVRADA is responsible for planning and conducting development, initial production, and product improvement of applicable items/systems, and providing technical support throughout the system's life cycle.

The recent AMARC reorganization (June 1978) has realigned the MM&T responsibilities within the Communications/Electronics area. The former Electronics Command, previously responsible for management of the total MM&T Program, has been reorganized into Research and Development and Readiness Commands (Communications and Electronics Materiel Readiness Command (CERCOM), Communications Research and Development Command (CORADCOM), and Electronics Research and Development Command (ERADCOM)). At the time of the reorganization, all existing MM&T projects were assigned to the R&D commands.

Mission: Improve Existing Techniques

CERCOM is the command responsible for follow-on procurement and support of all communications/electronics equipment. Its MM&T mission is concerned with the development of manufacturing processes, technologies, and equipment for use in production. Special interest is directed toward improving existing production techniques, as contrasted with the R&D commands' interest in bridging the gap between R&D and quantity production. "Return on Investment" and wide applicability in industrial production are the major considerations.

All Facilities in Private Sector

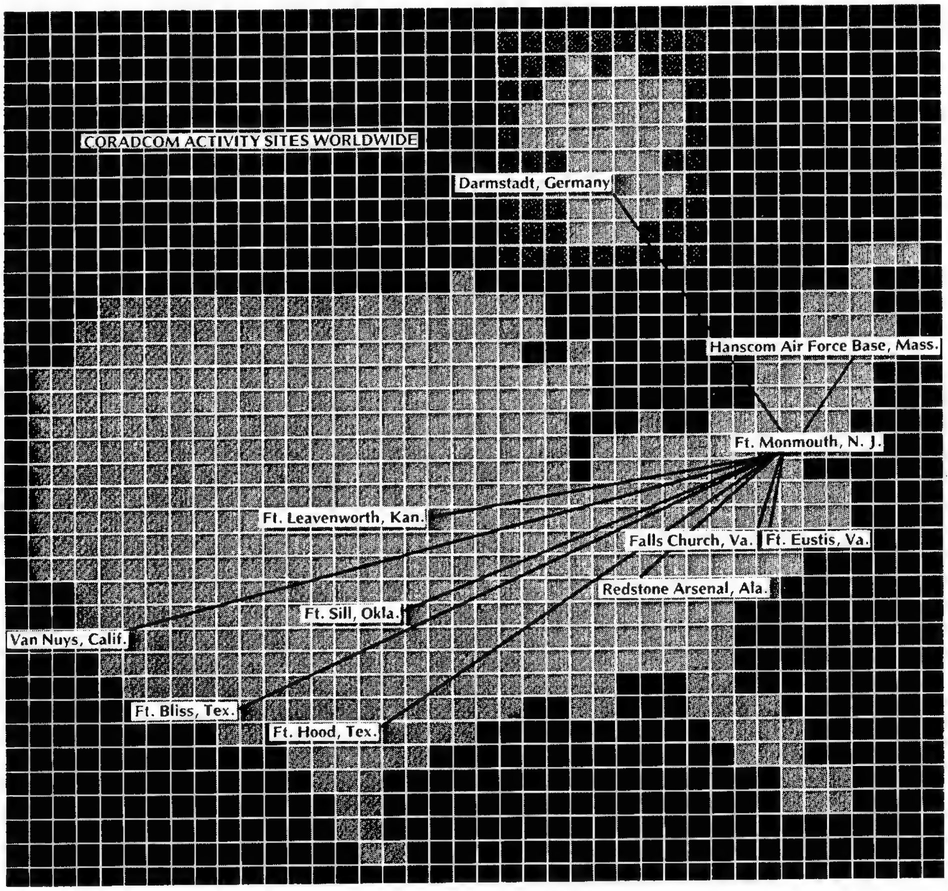
The communications/electronics area is somewhat unique within the Army in that total manufacturing and production capability lies within private industry. There are no arsenals or "captive" production lines. Depot operations are essentially concerned with supply, maintenance, and rehabilitation of equipment rather than manufacture. It is also interesting to note that almost 80 percent of the industrial firms concerned with production of communications/electronics equipment are small businesses. Many of these are new companies with large investments.

MM&T projects are needed for application of new and more efficient manufacturing methods, techniques, and processes (including improvements in testing and inspection methods) which will result in increased productivity, reduced lead times and cost, and improved reliability. Consideration should also be given to enhancement of safety, anti-pollution and energy conservation measures, and general advancement of the state of the art in manufacturing methods and procedures.

Domestic Capability Mandatory

The initial response from industry with MM&T proposals since our reorganization has been slow and somewhat disappointing. One of our major concerns continues to be increased dependency of U. S. manufacturers on foreign production technology and sources. We look to the U. S. manufacturer of electronic materiel as the source who can best identify problem areas in current manufacturing processes and work with us to establish MM&T projects.

Improvements in manufacturing technology should not be totally devoted to the new and exotic developments. There continues to be a need to improve basic manufacturing processes such as flow soldering techniques, production line testing, and quality acceptance procedures. We are obligated to maintain an industrial base that can meet our current needs and potential mobilization requirements for equipments that are in some cases based upon twenty year old technology, as well as for those new systems employing the latest state of the art.



CORADCOM Links Labs to the Field

Command, Control, and Communications

ALBERT J. FEDDELER coordinates the CORADCOM MT Program in his position as Engineer in the Technical Programs Office at CORADCOM. He received the B.S.E. Degree in Chemical Engineering at the University of Michigan. His professional experience includes service as Engineer with the Times Facsimile Corp. subsidiary of the New York Times Company, Development Engineer for the Linde Division of Union Carbide Corp., and Division Engineer for the Gubelman Division of Nashua Corp. His association with Army electronics programs at Ft. Monmouth, N.J. comprises several periods totaling 20 years. He is a member of the American Chemical Society and is a Registered Professional Engineer in New Jersey.

Three hundred military personnel and fifteen hundred civilian employees—over half of whom are engineers and scientists—keep things humming at the Communications Research and Development Command (CORADCOM).

CORADCOM is headquartered at Fort Monmouth, New Jersey, and is primarily responsible for the research, development, and initial acquisition of Army command, control, and communications (C3) systems and software support. In conjunction with its primary mission, CORADCOM's research and development centers carry out advanced, sophisticated research to maintain a technology base for communication and automation equipment. They also provide engineering support in the design of C3 systems in which this equipment is used.

The **Manufacturing Technology** program is planned to establish required manufacturing technology for future production needs in such areas as vibration resistant and low cost, high stability crystals; miniature and microprocessor controlled crystal oscillators; cable assemblies, emitters, and longer wavelength detectors for fiber optics; thin film electroluminescent displays; computer aided design/manufacture of custom LSI circuits; multilayer folded circuits; and printed page reformatting to electronic display compatible storage media.

Systems Oriented Mission

CORADCOM's primary mission is to develop and acquire C3 systems which will give the battlefield commander help in perceiving his battlefield, planning his operations, allocating and sustaining his forces, and successfully engaging the enemy. Three centers carry out this mission.

CENCOMS (Center for Communications Systems) conducts basic and applied research and engineering development related to communications systems and equipment. Research interests include propagation in the VLF through optical wave lengths, guided transmissions, antennas, modulation processes, and ECCM technology as related to digital communications.

Major technical thrusts include fiber optic cable systems, millimeter wave radio, and digital distribution systems.

CENTACS (Center for Tactical Computer Systems) has been established as the Army center of excellence for tactical computer systems technology. The center has a threefold mission:

(1) Conduct technology based research and development in tactical computer sciences and systems.

(2) Develop hardware and software for multiple application tactical computer systems.

(3) Provide technical assistance to Project/Product Managers.

CENSEI (Center for Systems Engineering and Integration) is responsible for the integration of battlefield computer systems. The center is involved with interoperability of all Army automated tactical command, control, and communications systems. Responsibilities include:

- Command, Control, and Communications Systems Engineering
- Cooperation with Army users to develop requirements and ensure effective use of advanced technology
- Interoperability and standardization planning at the Army, Joint, DoD, national, and international levels
- Maximization of intersystem compatibility and commonality
- Support of joint and intra-Army testing
- Management of Army use of frequency spectrum.

PMs Shoulder the Load

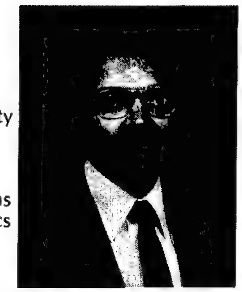
CORADCOM system developments are managed by Program/Project/Product Managers (PMs) falling into two broad groups—Army Tactical Data Systems (ARTADS) and Communication/Test PMs. Within the ARTADS Program are four project managed systems which are based on tactical computers. Five project/product managers (Communication/Test PMs) are developing families of systems to satisfy Army requirements for communications and test support equipments.

PROGRAM FUNDING

CORADCOM's major missions are funded by three Congressional appropriations—RTDE, Procurement, and OMA. The funding is divided so that ninety percent of the money goes to Procurement and R&D. In 1979 Procurement received over 61% of all appropriations, with 34% going to RDTE and the remaining 4% allocated to OMA. The total appropriation amounted to $521 million.

1980 Funding Increased

In 1980 the total appropriation is $494 million, with 56% in Procurement, 38% in RDTE, and 6% in OMA. The OMA portion reflects the support required to satisfy the mission responsibilities as well as software support to fielded equipment.



JOSEPH A. KEY is Project Officer, Manufacturing Technology, at the U. S. Army Electronics Research and Development Command, where he is responsible for management of the MM&T and MACI program for all ERADCOM laboratories and activities. This activity involves program formulation, justification, budgeting, execution, reporting, and general administration. From 1959 to 1972, he conducted studies on the effects of nuclear weapons radiation on Army communications/electronics devices and equipments. From 1972 to 1978, he was a member of the laboratory technical staff and had program coordination responsibility for product improvement, configuration management, developmental testing, producibility engineering and planning, and manufacturing technology. He received his B.A. in Physics in 1958 from Drake University and an M.B.A. in 1974 from Rutgers University.

ERADCOM Provides the Means

Eyes, Ears, and Stingers

The primary function of the U. S. Army Electronics Research and Development Command (ERADCOM) is the research, development, and acquisition of electronic materiel. ERADCOM is the Army's first single command to be given total responsibility for developing electronic materiel for intelligence, surveillance, and target acquisition on the battlefield.

Although ERADCOM has total responsibility it does not operate in a vacuum. It relies upon the skills of private industry to help develop this materiel and it seeks guidance from the users of its products—the soldiers in the field. Contributions are also made by several other government agencies. The information provided by these sources is correlated by the ERADCOM Systems Engineering, Planning, and Analysis Directorate, which gives direction to each laboratory.

Survivability Critical

ERADCOM ensures battlefield success for the Army in three ways:

(1) By providing equipment for seeing the battlefield and finding targets through the use of Sigint, Radars, Rembass (sensors for remotely piloted vehicles), Meteorology, Night Sights, and Electro-Optics.

(2) By providing equipment for neutralizing the enemy—using Fuzes, Jammers, and Spoofers.

(3) By improving survivability of materiel through ECCM techniques, NWE hardening, and Electronic Technology.

The current ongoing MM&T and MACI program through FY-80 consists of 69 projects funded at $34.6M. The primary thrust of the program is to develop manufacturing technologies for the establishment of a production base in support of procurement of ERADCOM systems. However, many projects within the program additionally support other Army and DOD tri-service critical electronic requirements.

The successful completion of these efforts will reduce cost, improve the reliability, and allow the timely production and procurement of such systems.

Joint Efforts Routine

ERADCOM is comprised of thirteen subordinate elements which are located throughout fifteen states, the Canal Zone, and Germany. These include seven laboratories, each of which is a full spectrum laboratory and each a center of excellence. However, they do not operate alone. For example, the Night Vision and Electro-Optics Laboratory concentrates on seeing the penetration of obscure battlefield objects in the dark. It works with the Atmospheric Sciences Laboratory in studying the effects of meteorological conditions upon electro-optical systems and lasers. In every case, the research done in the laboratory contributes toward ERADCOM's overall objective—to give our soldiers on the modern battlefield the capability to locate and neutralize the adversary.

Consolidation for Cost Effectiveness

ERADCOM was established to consolidate the activities of the Harry Diamond Laboratories, the R&D segments of the U. S. Army Intelligence and Security Command, and the U. S. Army Electronics Command. The purpose of this consolidation was to make the best use of the taxpayers' investment.

Harry Diamond Laboratories, which was the first of the seven laboratories associated with ERADCOM, is located in Adelphi, Maryland and employs approximately twelve hundred people.

The next largest laboratory is the Night Vision and Electro-Optics Laboratory, which is in Fort Belvoir, Virginia, and employs five hundred fifty personnel.

Battlefield Intelligence A Prime Task

Three ERADCOM laboratories are in Fort Monmouth, New Jersey. They are the Electronic Warfare Laboratory, the Electronics Technology and Devices Laboratory, and the Combat Surveillance and Target Acquisition Laboratory. The largest of these is EWL, which employs approximately five hundred persons. Two hundred perform electronic warfare vulnerability analysis at the Office of Missile Electronic Warfare in White Sands, New Mexico, and fifty are assigned to the Intelligence Materiel Development and Support Office, Fort Meade, Maryland.

The remaining two laboratories under ERADCOM's command are the Signals Warfare Laboratory, located in Virginia, and the Atmospheric Sciences Laboratory in White Sands, New Mexico.

Project Managers Specialize

In addition to the laboratories, ERADCOM is assigned four project managers who devote specialized attention to management and fusion of SIGINT/EW sensors (CAC), mortar and artillery locating radars (FIREFINDER), battlefield sensors (REMBASS), and stand-off target acquisition systems (SOTAS).

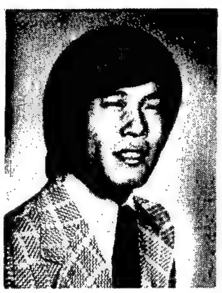
This organizational structure is fulfilling the ERADCOM mission:

- Tactical intelligence, surveillance, and target acquisition
- Electronic countermeasures
- Electronic fuzing
- Electronics technology.

Low Cost, High Quality Standardization

Analog Systems Testing

JEFFREY KUNG is a Section Head of Test Program Set Engineering at the PRD Division of the Harrison Corporation in Syosset, New York, where he is responsible for AGEN programs as well as other projects involving testing. He holds a BEEE Degree (1970) and an MEEE Degree (1972) from the City University of New York and an M.S. in Engineering Management (1978) from C. W. Post College of Long Island University. He has been active in automatic testing programs at PRD since joining that firm in 1972. Prior to that he taught electronics for two years at the RCA Institute, and for three years at the Alphanumerics Corporation he designed digital and sweeping systems for phototypesetting equipment.



BENJAMIN SANG is a Project Engineer in the AGEN program at the PRD Division of the Harrison Corporation in Syosset, New York, where he designs the top down structures of the AGEN software and personally programs most of the FORTRAN modules in the AGEN executive program. He has worked at PRD since 1973, after several years of computer experience at the Chase Manhatten Bank and Canon Camera. He holds a BEEE from the City College of New York and an MBA in Computer Methodology from Baruch College of the City University of New York.

An interactive computer programming aid that automates testing of analog systems has been developed by PRD Electronics, a division of Harris Corporation. The device generates test program sets in a high level language for evaluating analog circuits used with automatic test equipment. Called the ATLAS Test Program Generator (AGEN), the system was developed under a U. S. Army Electronics Command contract. Its use minimizes both human effort and computer time in developing analog test sets. PRD has found that they can reduce manhours for generating test program sets by nearly 90 percent. For example, a program requiring 200 man-hours of experienced engineering time for manual generation takes only 22 hours for AGEN generation.

Manual generation has generally been a way of life in developing analog test programs, with computer generated tests confined largely to digital circuits. However, this approach is both time consuming and costly, and the uniformity and quality of programs has been little more than acceptable; an automated approach has been badly needed.

Less Computer Time Required

AGEN eliminates the repetitive, structured tasks of manual test generation. Not only does it reduce costs, it minimizes delays (less computer time means less downtime), encourages standardization, and improves the quality of testing procedures. Another major advantage is its ease of utilization, with only circuit specifications needed as input. The AGEN user does not need a background in circuit analysis or programming.

Originally demonstrated on RF amplifiers and oscillator circuits, AGEN has been extended to cover a much larger class of circuits—audio amplifiers, filters, mixers, and power supplies. It can also be extended to couple different circuit types.

Comparison With Conventional Systems

AGEN savings are clearly demonstrated when we consider the steps in generating test program sets. Figure 1 shows these steps for a conventional manual system. This figure also reflects the average percent of the total effort required to complete each task. Generating a typical analog circuit program requires one to two man-months.

During steps A and B, the user collects the test requirements for the unit to be tested. Using a near English source program language, he or she converts these requirements into a set of instructions—i.e., a test program (steps C, D, and F). A description of required voltage and current values, interface device data, and signal/source/measurement device data are then generated (steps E and G). A translator converts the test program into an executable object code which, through the station operating system, controls execution of the test in providing the stimuli, making the measurements, analyzing the results, and performing the decisions (steps H and J).

Programmer Decision Necessary

Debugging (step K) follows, with the complexity of this task depending on the difficulty of identifying the program error. A program error can be either a test program logic error, improper use of the test system, or incorrect test strategy. It can be identified by either the compiler during the translation process or by the test engineer whenever program execution on station fails to produce the expected result.

When the expected result is not obtained, the programmer must determine whether this is because of an error

Automated

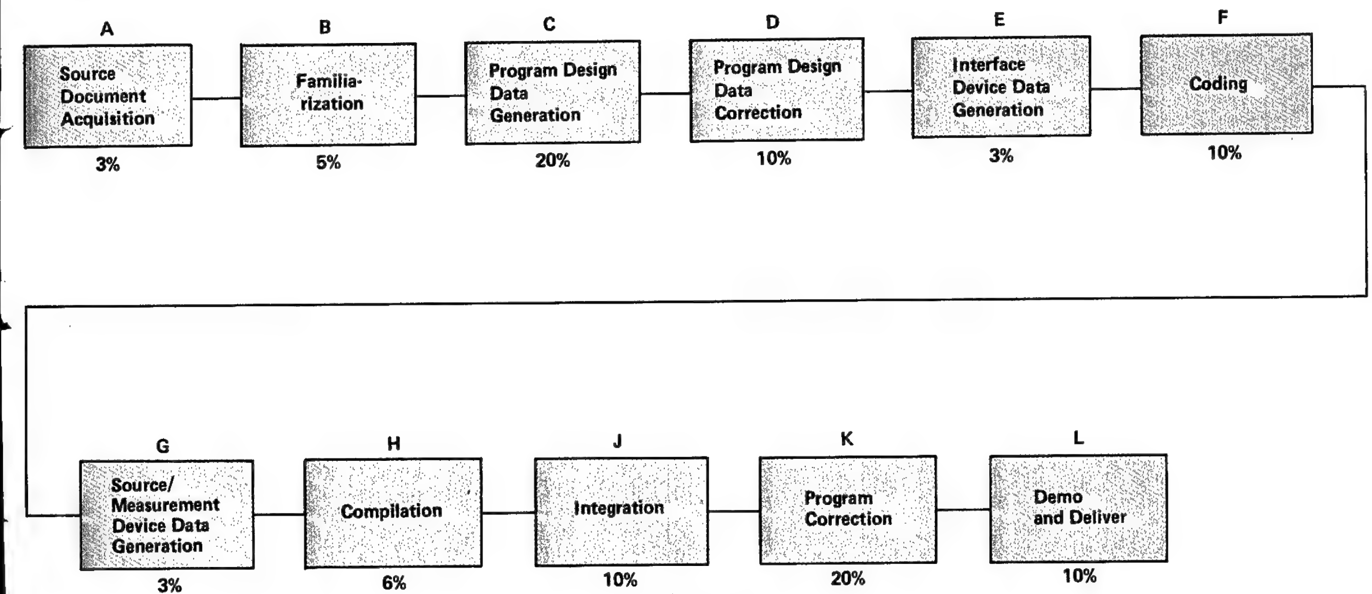


Figure 1

in the test program, improper use of the test system, incorrect test strategy, a test system failure, or failure of the unit and interface device being tested. User performance during manual generation of a test program depends heavily on one's ability to develop a good test strategy and one's understanding of the programming language.

Language Related Errors Erased

AGEN, on the other hand, requires only a knowledge of the test specifications of the analog module and insertion of operating parameters interactively. Highly effective test procedures based on an optimum test strategy for testing each analog circuit are built into the system and are no longer the user's responsibility. As shown in Figure 2, AGEN requires only four steps for test program generation—A, E, and H from the conventional approach, and an additional step, X, for interaction with the computer. Using AGEN reduces the total effort for generating programs by more than 85 percent. The resulting programs are of an optimal quality and free of any syntax or semantic errors. Since the user provides only some numerical values or units, most of the language oriented errors that often occur during user/computer interaction are eliminated.

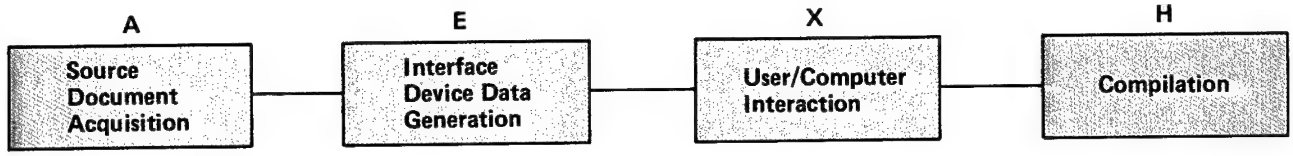


Figure 2

System Description

AGEN is written in FORTRAN IV and is executed on a batch or time share system having a FORTRAN compiler. Although it covers only a few of the several hundred network, subcategory, and characteristics codes, it serves as a guide for future expansion. It provides the entire framework of a well defined modular, top-down structured system. Generating an ATLAS tape program for any other code requires only simple extension to create other branches.

In order to create a test program under AGEN, the user

- Examines the circuit
- Determines which characteristics to test
- Lists parameters
- Lists required power voltages
- Interacts with AGEN executive, inserting the parameters by answering the questions.

AGEN is written in a modular fashion, as shown in Figure 3. The common data base structure consists of a set of arrays used to store data and calculated values for input to the automated test equipment subroutine. Software modules in the AGEN system perform as follows.

DNSC determines the appropriate codes for the network, the subcategory, and the characteristics to be tested by questioning the user. A user who does not know the code in question can call up a list from which to select the proper number.

IVT collects the required input values and the acceptable tolerances of the expected outputs. In response to computer query, the user gives the minimum number of input parameters required to generate a reasonable test for the particular code. It calculates the expected values of the outputs (for all test inputs) at the specified tolerance within which test unit measurements must fall. The expected outputs, with upper and lower limits, are stored in an array of calculated values.

OTPT serves several functions. It

- Searches the ATLAS LIBRARY and inputs the test source program to computer memory.
- Inputs the variables established by IVT in appropriate format.

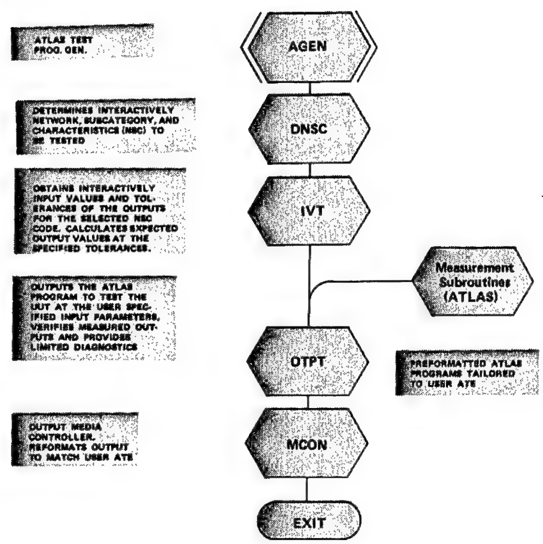


Figure 3

- Inputs user selected units at the required places in the test program.
- Outputs the completed source to a file location so it can be written onto magnetic tape.

Subsequent compilation produces an object program tape, listing priorities, that is input to the test equipment source language program for execution.

Flexible Alternatives Provided

AGEN is designed with horizontal and vertical expandability. Horizontally it can be expanded to include more networks than the current five. Vertically it can include more characters within each network. In addition, AGEN is independent of the ATE station. The only modules that need to be changed from one type of ATE to the other are the measurement routine (ATLAS) and the OUTAPE as shown in Figure 3.

Production Capability Established

SAW Devices Batch Processed

Using lithium niobate and/or ST quartz substrates, the U. S. Army Electronics Research and Development Command has successfully established production capability of surface acoustic wave (SAW) devices for the first time. In the milestone ERADCOM project, Hughes Aircraft Company designed, fabricated, and tested six devices. Finally, the company established a pilot line capable of delivering one hundred fifty of each of the device classes.

Prior to this three year program, SAW devices were typically fabricated in a laboratory environment in small quantities. Further, cost information for volume production was nonexistent. The test efforts have demonstrated a wide variety of reliable devices which can be made in relatively modest quantities at reasonable cost. These results have had a dramatic impact upon SAW production for military system programs.

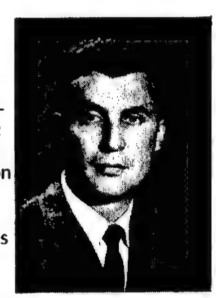
Out of Laboratory Into Use

The significant potential offered by SAW devices for enhanced signal processing capability (along with increased reliability and reduced size and cost compared with alternative technologies) has effected the increased use of SAW devices and subsystems in a variety of military and commercial system applications. Prior to the initiation of this program, devices with electrical performance characteristics comparable to those proposed under the program had been developed in the R&D laboratory. However, facilities or techniques for batch processing SAW devices did not exist; likewise, process specifications and crystal/transducer documentation procedures had not been developed. Typical devices had yet to be screened to MIL-STD-883B types of environmental requirements.

Prior to the MM&T program, machined SAW packaging generally provided good suppression of spurious electromagnetic feedthrough; however, their high costs made them unsuitable for military systems produced in quantity. The MM&T effort on SAW devices was initiated in 1975 in recognition of these problems, whereby the program sought to implement an effective production capability, identify environmental constraints, and provide guideline manufacturing cost data for future SAW device procurements.

Program efforts were purposely restricted to a representative set of SAW devices which operated at frequencies that did not exceed the state of the art in photolithographic capabilities but nevertheless required a meaningful design and fabrication challenge.

ELIO A. MARIANI is Leader of the Acoustic Signal Processing and Devices Team, U. S. Army Electronics Technology and Devices Laboratory, Electronics Research and Development Command. His current efforts relate to signal processing devices and processors using surface acoustic wave, shallow bulk acoustic wave, and bulk wave device technology. Mr. Mariani has previously conducted projects dealing with microwave filters and coupling structures. He is a member of the IEEE Sonics and Ultrasonics Group, and he serves as an Associate Army Member to the Advisory Group on Electronic Devices (AGAD). Mr. Mariani received his B.E. of Electrical Engineering from Drexel Institute of Technology in 1960.



Four-Phase Program Laid Out

The purpose of the program was to establish a production capability for SAW devices of varied design and material, whereby six device classes were specified with strict electrical and environmental requirements. The device classes included bandpass filters, phase-coded tapped delay lines and linear FM pulse compression filters with center frequencies of 100 and 200 MHz using lithium niobate and/or ST quartz substrates.

The program effort was divided into four phases. During the engineering phases (I and II), six devices were designed, fabricated and tested. Design modifications were implemented, as required, where first phase samples failed to meet specifications; this resulted in the finalization of the electrical specifications for the balance of the program. The third (confirmatory sample) phase consisted of testing these devices according to MIL-STD-883 type environmental stress at a specifies sampling rate. The final phase established a pilot line production capability.

Phase I — First Engineering Samples

During the initial portion of the program the electrical design, fabrication, and electrical testing of six device classes was performed and ten of each device type were demonstrated and delivered. The six categories are summarized in Table 1. These design categories are representative of the major current and potential applications of the technology.

Each device design was verified to be consistent with the specification requirements via computer simulation prior to mask making. An Electromask fixed reticle pattern generator was used to generate 10X emulsion reticles, with 1X antireflection chromium masks stepped and repeated using the image repeater software of the same piece of equipment. A typical layout is shown in Figure 1.

Reliability Improved

The required series and/or shunt resistive tuning elements necessary to meet the voltage standing wave ratio (VSWR) specification are shown in the mask layout in Figure 1. Note the use of thin film aluminum metallization to effect the tuning resistors, which form part of the transducer pattern. The approach provides significant labor savings—plus improved reliability—by reducing the number of interconnections. Three resistor taps were used to account for uncertainties in the sheet resistivity of the thin film aluminum and also variations in final series resistance requirements. The various resistor taps were opened by using a diamond scribe.

Designation	Device Class	Substrate Material	Center Frequency	Package Marking
BP-Q	Linear Phase Bandpass Filter	ST-Qtz.	100 MHz	B-Q-10-02
BP-LN	Linear Phase Bandpass Filter	$LiNbO_3$	150 MHz	B-L-15-30
PC-Q	Linear FM Pulse Compression Filter	ST-Qtz.	150 MHz	C-Q-15-50
PC-LN	Linear FM Pulse Compression Filter	$LiNbO_3$	150 MHz	C-L-15-50
TDL-100	Biphase Coded Tapped Delay Line Filter	ST-Qtz.	100 MHz	T-Q-10-10
TDL-200	Biphase Coded Tapped Delay Line Filter	ST-Qtz.	200 MHz	T-Q-20-10

Table 1

Manufacture of the devices made use of substrate materials obtained from Valpey-Fisher Corporation (ST quartz—using 3 X 0.75 X 0.025 inch plates with ± 15 min. orientation to the X axis) and from Crystal Technology, Inc. (lithium niobate—using two inch diameter by 0.020 inch thick plates with ± six min. orientation to the Z axis). The surface roughness of the crystal plates did not exceed 6.3 micrometers (250 microinches). The top crystal surface then was polished so that examination at 250 X would not reveal scratches, pits, or other blemishes.

Normal Fabrication Methods Used

The device processing steps followed the commonly accepted procedure for integrated circuit fabrication; the SAW process chart is listed in Figure 2. The individual device die were mounted in machined aluminum packages using Dow Corning 3140 RTV and air cured for 24 hours. The assembly operation was completed with the thermocompression bonding of one mil diameter gold wires to the thin film aluminum transducer pads. The requirement for confirming the device design during the initial phase of the effort necessitated the use of machined aluminum packages with SMA connectors.

Typical test results achieved during Phase I are shown in Table 2, which compares specification requirements with the averages of electrical test results. The primary problem area was the failure of most of the six designs to simultaneously meet the insertion loss and VSWR specification.

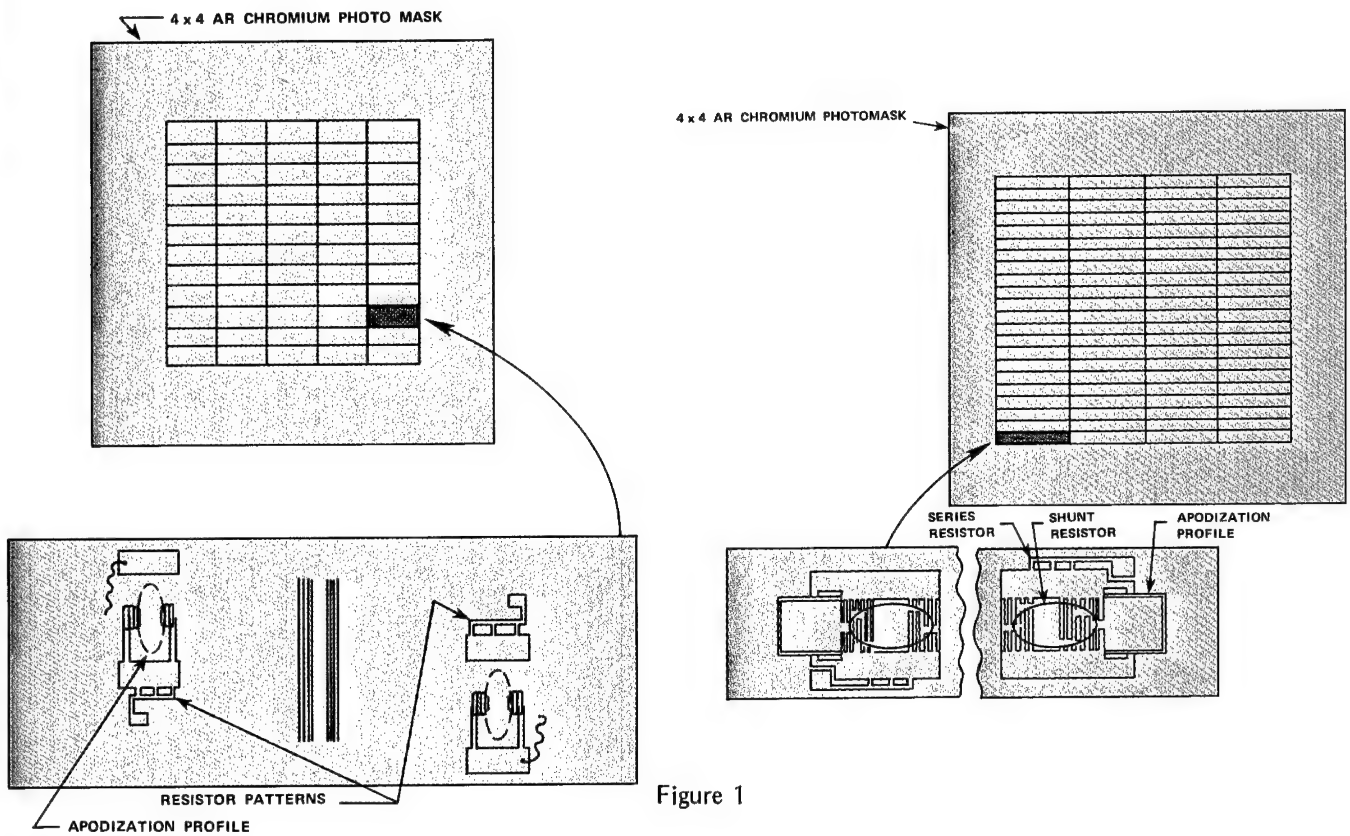


Figure 1

Phase II—Second Engineering Samples

The second phase of the project involved a redesign effort in order to satisfy the original electrical specifications. It was determined in some cases that the specified parameters could not be theoretically met, primarily because of the tradeoff between VSWR and insertion loss. Hence, those parameters were respecified to avoid substantial device costs projected for more complex matching networks. Moreover, the impact of VSWR on system performance at intermediate frequency was demonstrated to be insignificant for most typical applications. Thus, the result of the Phase II effort was finalization of the electrical specifications for the remainder of the program.

In order to make better use of the substrate material, the substrate sizes and masks were revised during the second phase. The ST quartz from Valpey-Fisher was changed to 2 X 2 X 0.025 inch, while the y-z lithium niobate obtained from Union Carbide was 2 X 1.75 X 0.020 inch.

Machined Packaging Replaced

Also, commercially available semiconductor (pin) packages from TekForm were implemented to replace

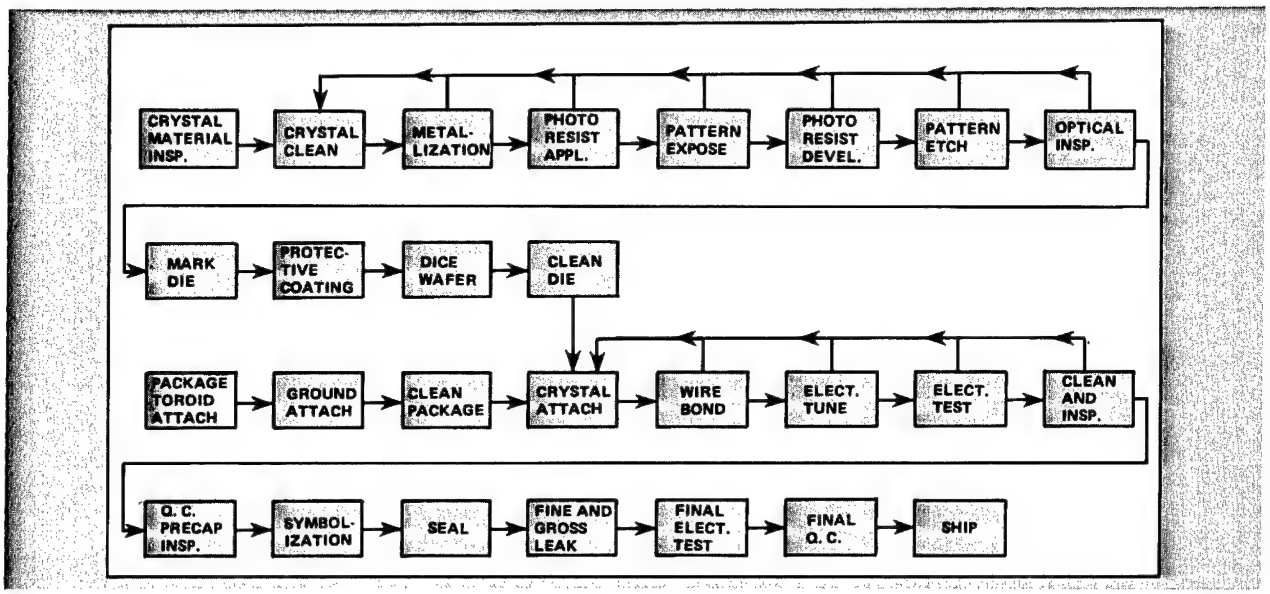


Figure 2

Comparison of Measured Parameters and Specifications For BP-LN Filter

		SCS-476	Measured
3.10.1	fo (MHz)	150 ± 3	150.0
3.10.2	β @ -3dB (MHz)	30 ± 0.6	30.0
3.10.3	τ (μsec)	2 ± 0.01	2.00
3.10.4	$\tau \times \beta$	60	60
3.10.5	Insertion Loss (dB)	15 ± 1.5	21
3.10.6	Sidelobe supp. (dB)	35	40
3.10.7	Feedthrough supp. (dB)	50	53
3.10.8	Spurious supp. (dB)	35	39
3.10.9	VSWR	1.5:1	<2.3:1

Table 2

the more costly machined package and to meet the hermeticity, moisture resistance, and temperature requirements. This phase was completed with the delivery of an additional ten devices for each of the six designs specified. The result of this effort was a functional adherence to the electrical specifications based on a cost effective package configuration.

Phase III -- Confirmatory Samples Tested

During the third phase of the program both the electrical and environmental commitments of the various devices were tested and conformity to specification was confirmed, using a MIL-STD-883 type of screening approach. The completion of this phase resulted in the delivery of fifty each of the six device types.

The SAW devices finalized during Phase III then were subjected to the numerous environmental stresses listed in Table 3. Test allocation, sample size of each lot of fifty devices, and accept/reject criteria are summarized in Table 4. The device failures did not exceed the number of rejects specified. Moreover, the failures attributable to environmental stress had no discernible pattern, in that failures detected at final electrical test appeared randomly.

Phase IV—Pilot Line Set Up

The reproducibility of specified electrical and environmental requirements for SAW devices in a volume produc-

Group	Test	MIL-STD	Method	Condition	Comment
I	Wire Bond	883	2011	D	2 gm tension
	First Electrical	—	—	—	—
II	Solderability	883	2003	—	—
III	High Temperature Storage	883	1008	A	72 hrs
	Center Frequency Insertion Loss	—	—	—	—
IV	Life	202	108	—	85°C
	Final Electrical	—	—	—	—
V	Hermeticity	202	112B	C A	Fine Gross
	Short Circuit				
VI	Vibration	202	201	—	Low frequency
	Short Circuit	—	—	—	
	Shock	202	213	I	—
	Short Circuit	—	—	—	
	Thermal Shock	202	107	A	10 cycles
	Short Circuit	—	—	—	
	Moisture Resistance	202	106D	—	50V DC
	Final Electrical	—	—	—	—

Table 3

tion environment was tested in the final phase of the program. A key result of this phase was the establishment of meaningful process yield, labor at each process step, and manufacturing cost data on each device type, including a comparison of this data with prior low volume efforts.

A capacitance probe test was evaluated in order to significantly reduce labor time associated with visual inspection of the wafers at 250X magnification. The purpose of the probe test evaluation was to determine the efficiency of a semiautomated approach to detect "short" and "open" defects in the SAW transducer patterns. A Fairchild Sentry 610 Integrated Circuit Probe Station was modified

Device Type	Group Test (Ea. Type)	Sample Size (Ea. Type)	Max. Detective
BP-Q, BP-LN, PC-Q, PC-LN	I	50	0
	II	12	0
	III	18	0
	IV	18	1
	V	12	0
	VI	24	2
TDL-100, TDL-200	I	50	0
	II	6	0
	III	9	1
	IV	9	1
	V	6	0
	VI	12	1

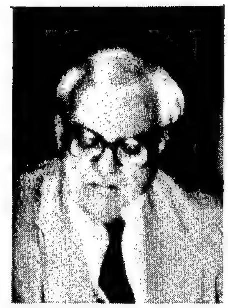
Table 4

for the measurement. A wafer of this type could be scanned in ten minutes, providing a printout which maps the capacitance value for each transducer. The capacitance probe technique proved to be effective for screening shorted transducers; an improvement in yield was noted over visual inspection. Previously, nonconductive debris on the surface of the transducer was misinterpreted as a metallization short which in turn led to circuit rejection. The data derived from transducers with open circuit defects was inconclusive. This was due to the fact that a nominal value of capacitance for a given design could not be established due to the capacitance of the probe card, which was on the same order of magnitude as the transducer.

Costs Established

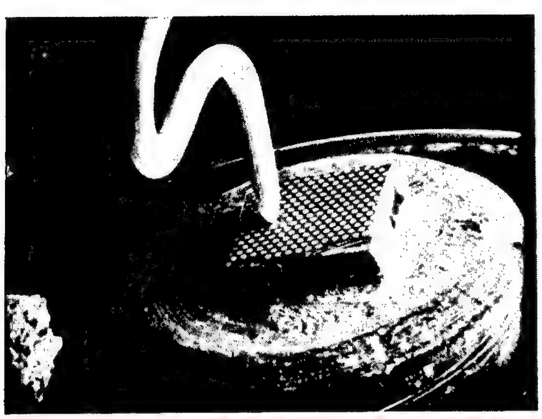
The manufacturing cost of the six device types, completely packaged and tested, is estimated to range from $75 to $125 in quantities of a few hundred, assuming improved yields and use of projection weld sealing of all device packages. These cost projections factor in the learning curve resulting from the MM&T effort. The cost of the quartz bandpass (BP-Q) and pulse compression filters should range near $75, while the phase coded tapped delay lines average closer to $125 due to larger device size. Overall, the package cost represents about one fifth of the manufacturing cost. Higher volume production should have a further impact on device cost. It is estimated that in quantities of 1000 the cost of the BP-Q filter should be $60 or less.

JAMES F. KELLY is a Project Engineer at the U. S. Army Communications Research and Development Command, where he is involved with production engineering and MM&T programs. During his past two years with CORADCOM and his previous eleven years with ECOM, Mr. Kelley worked on the automation of GaAs diode fabrication, automating the optical inspection of PC boards and hybrid substrates, development of pulsed IMPATT diodes, and the online testing and adjustment of electronic assemblies in addition to many other projects. After receiving his B.S. in Electrical Engineering from Pennsylvania State University in 1953, he pursued graduate studies there and at the City College of New York. He also worked at the Army's Tobyhanna Depot in Pennsylvania until 1964.



Devices Used In Future Designs

Oscillator Production Rates Zoom



75X

Production of new oscillator assemblies rose as much as 97.8 percent as a result of a U. S. Army Electronics Research and Development Command manufacturing technology program on gallium arsenide semiconductors. The MM&T program objective was to not only reduce costs but also to increase the reliability, capability, and availability of various classes of these devices. Several paths were followed in the program which led to marked technology advances, culminating in sharp improvements in both operational parameters and automation. The program extended from 1969 through 1978.

These programs resulted in devices which are now successfully employed in passive (detector/mixer) or active (GUNN or IMPATT diode generator) applications in modern radar systems. So dramatic were the economic and technical improvements that these semiconductor devices are being committed to yet newer designs as well as being retrofitted to existing systems.

Among the most notable programs for advancing semiconductor technology in recent years were those involving

- Techniques for an automated system to detect semiconductor contaminants occurring throughout device fabrication
- High burnout resistant mixer diodes
- A new reactor and automation techniques for growing the n- and p-type GaAs epitaxial layers necessary for diode production
- Low noise local oscillators for portable radar systems.

Contaminants Quantified, Controlled

This program successfully established techniques for detecting and quantifying unknown trace impurities that contaminate and degrade crystalline structures in semiconductor devices during production.

To increase production yields, reduce costs, and improve performance of these devices, ways were sought to detect and control incursion of contaminants into semiconductor materials by applying the fault detection and isolation methods common to the field of Automatic Test Equipment.

Typical semiconductor manufacture is accomplished through batch processing entailing 25 to 30 production steps. If contaminant concentration can be measured during this production, poor semiconductor performance can be predicted; however, only a few production steps lend themselves to such measurement. Moreover, where tests on semiconductor materials can be made, they are generally destructive.

Several avenues of contamination were studied in the program. They included (1) the assumed presence of impurities in reagents and solvents used in manufacturing; (2) airborne contamination during wafer immersion in acids and deionized water; and (3) impurity ingress during material handling. Water rinsing operations were also considered—dissolved ionizable gases, dissolved nonionic ionic gases, organics, particulate matter, and ionizable salts all were identified as potential contaminants in water.

Impurities Assumed, Accepted

Impurities were assumed to exist to a large degree in the various reagents, solvents, and other chemicals used in the manufacturing process. The impurity concentration in the reagents as well as the transfer ratio had to be determined.

In depth chemical analyses were considered to be both impractical and expensive and would soon have outrun economic gains accrued from improved product yield. Thus, the program was aimed at providing the necessary control data within economic constraints of improved yield.

Several electrical measurement methods were therefore used. They included V_B readings, I-V characteristics observations, lifetime measurements, and high temperature reversed bias stressing tests. These, combined with the heart of the automatic analytical test system—the Jarrell-Ash Plasma Atomcomp Spectrometer—provided a powerful tool for identifying semiconductor material contamination. This spectrometer can detect impurity levels in reagents and particulate matter and can analyze all chemical inputs, liquid and gaseous, both quantitatively and qualitatively. The system can

- Provide early warning of excessive contamination
- Allow contaminated material to be discarded (rather than accrue further manufacturing costs)
- Identify critical contaminants and threshold levels
- Provide lot traceability during processing to correlate final yields of end products with known contamination levels
- Incorporate additional sensors to monitor temperature, flow rates, real time gas stream, pressure, and residual pressure under high vacuum.

Historical information on the performance of a piece of equipment, comparison with present performance, and trend information all can be obtained readily at very low cost.

High Burnout Resistant Mixer Diodes

Noteworthy improvements were realized as a result of this program to engineer and fabricate reliable mixer diodes for radar equipment operating in the S-, X-, and Ku-band frequencies.

The usual mixer device at microwave frequencies is a crystal mixer, either point contact or Schottky barrier. The Schottky barrier type diodes, with rectifying metal-semiconductor junctions formed by plating, evaporating, or sputtering various metals on n-type or p-type semiconductor materials, are preferred in applications above X-band frequencies. Generally, n-type GaAs semiconductor materials are used in their fabrication.

Advantages of Schottky diodes include superior noise figure, especially at low IF (Doppler) frequencies, as well as better mechanical environmental reliability when compared with equivalent point contact diodes. However, Schottky diodes have traditionally proven less resistant than point contact diodes to RF burnout (noise figure degradation) in high frequency radar systems where high power RF pulses often are incident on the diode.

Reliability, Resistance Improved

Reliability and burnout resistance of these Schottky diodes, however, were improved in the program. Here, the diode structure was changed by fabricating guard rings around the periphery of the metal dot in GaAs type diodes for Ku-band frequencies. Diodes fabricated as such did not exhibit parasitic losses and showed a 3 dB improvement in burnout. (Additionally, test data showed that inverted mesas have improved CW burnout at S-band frequencies.) The Schottky diode is illustrated in Figure 1.

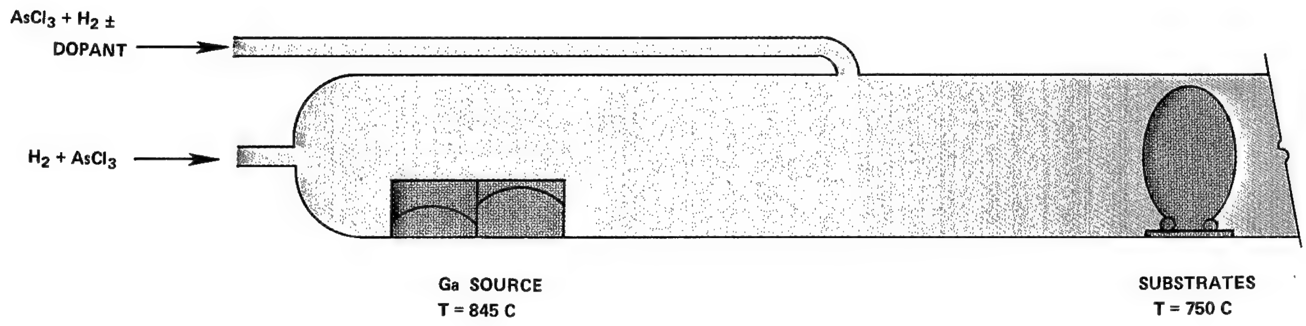


Figure 2

In general, such improvements were possible as a result of the following recent advances:

- Better control over semiconductor purity
- Epitaxial material of low series resistance
- Photolithographic techniques to achieve compact areas for Schottky diodes.

In practical application, these improved diodes now can replace the conventional MIL standard point contact diodes. The Schottky barrier diodes are produced in the standard IN23 ceramic package for the S- and X-bands and in the standard IN78 coax package for the Ku-band. RF burnout tests on the new diodes, which were made with titanium Schottky barrier junctions, exhibited marked improvement in burnout capability over the standard point contact diodes.

Epitaxial Material Growth

Three programs showed promising results in establishing techniques that provide low cost fabrication of high frequency negative resistance diodes with a dopant profile which is referred to as low-high-low (LHL). Two of the programs were concerned with a single layer construction utilizing n-type material, and the third addressed double layer construction and is referred to as a double drift. The latter construction required the utilization of p-type semiconductor material grown epitaxially on n-type. Epitaxy is a growth technique in which the crystal structure of a substrate can be extended by vapor phase deposition of additional atomic layers of the same material.

Specifically, the first two programs culminated in establishing automation techniques and the use of computer control systems for growth of n-type GaAs epitaxial material crucial to production of the GaAs, LHL, IMPATT diodes. Automation techniques were successfully developed involving sensor placement, software programs, measurements, data flow, and chip handling. The control system features improved gas and vapor controls that eliminate deficiencies in existing systems, thereby enhancing the level of control necessary for the desired results.

Stemming from the improved techniques of the above programs, the third program then established procedures for growing p-type material upon an n-type epitaxial layer (double layer construction). A new and successful reactor (used for growing epitaxial layers) was designed which utilizes a separate gas port for the p-type material.

The epitaxial layer upon which the operation of IMPATT diodes depends is grown in the reactor shown schematically in Figure 2. The principle of operation is such that $AsCl_3$ passes over the molten Ga, forming GaAs vapor. This vapor then is deposited on the GaAs substrate since it is at a lower temperature. Epitaxial layer growth has started. After a fixed time the dopant gas is allowed to flow into the reactor—the required dopant layer now is being formed. The flow of the dopant gas then is terminated and the dopant spike has been formed. The ability to rapidly turn the dopant flow on and off determines the spike width, and the height is determined by the dopant concentration in the gas. Critical to this process is the flow rate of the gases, the concentration of the specific gases, the temperature throughout the system, and the time required for each sequence. In Figure 2, only n-type material is grown. By placing monitoring sensors at the proper location in the system, all of the critical parameters can be controlled to a very close tolerance, resulting in uniform devices.

Requirements Met

The results to date on the single layer construction have been outstanding: the epitaxial material, which was grown in a newly designed computer controlled reactor, had a higher degree of uniformity and reproducibility than material made previously using research type reactors. Peak (large doping) concentrations can be reproduced with the following deviations: peak inverse, ± 5 percent; peak position, ± 5 percent; and peak width, ± 6 percent. The growth rate has a reproducibility deviation of less than ± 7 percent. The reproducibility for equilibrium structures results in at least 90 percent yield to a variation of 10 percent.

The engineering samples to date have exhibited the desired requirements: 3.5 watts CW minimum power output, operating frequency between 9 to 11 GHz, efficiency of at least 20 percent, and a junction temperature of 200 C maximum.

The initial capability of the newly designed reactor mentioned previously has also been demonstrated in double layer construction, in which p-type layers were successfully grown in conjunction with n-type layers.

Low Noise Local Oscillators

The challenge to develop a low noise Ku-band gallium arsenide diode oscillator for use as a local oscillator in portable radar was successfully met in spite of virtually nonexistent state of the art production methods prior to this particular program. The oscillator was to be designed using the high quality sealed design approach and was required to maintain good frequency stability over temperature. The Ku-band source was to be mechanically tunable from 14.4 to 15.3 GHz, with electronic tuning for AFC purposes. The local oscillator was to have low AM noise, i.e., AM noise was to be at least 115 dB below the carrier at 1 KHz from the carrier in a 1 KHz bandwidth (single sideband).

The initial design approach was to utilize a basic half wavelength cavity that was iris coupled to the external load. The iris could be readily adjusted to control the loaded Q, which would not exceed 500 at mid-band. Both IMPATT and varactor diodes were to be mounted on posts in the cavity, and the post diameters and positions were to be determined to provide the requisite coupling between each diode and the cavity.

Deficiencies Resolved

The iris coupled high Q cavity was fabricated, tested, and analyzed. Preliminary results indicated deficiencies associated with the bias lead contact and choke. Also, experiments indicated that loss (Q) of the tuning varactor affected the frequency and power output. Alterations—including an improved copper block oscillator body construction, a temperature compensated mechanical tuner, and a new bias lead folded choke design—eventually led to a device that exhibited generally satisfactory performance for use with IMPATT diodes.

This program was later modified to include X-band GUNN diode oscillators. Such oscillators were designed to be mechanically tunable over 200 MHz and electronically tunable over a minimum of 20 MHz for AFC. The frequency/temperature coefficient was designed to operate from -25 C to +70 C, to accept a vibration level of 1G max from 5 to 20 Hz, to accept shock of 15 G max for 11 msec in any direction, and to operate at 55 C under 97 percent humidity. Tests on 20 units showed compliance with these specifications.

The final oscillator design employed in the program incorporated GUNN diodes and brazed cavities so as to meet cost targets and performance requirements. In addition, the design of these solid state local oscillators incorporated a built-in attenuator for power lever set and accomplished electronic tuning through a varactor diode.

The Ku-band and X-band oscillators were tested to MIL-Spec environmental conditions and both units successfully met the specifications. The performance of the final GUNN oscillator was much improved over that of the initial IMPATT diode oscillator. Considerable improvements were also made regarding yield, costs, and technical performance.

New Standard Specified

The estimated yield of the Ku-band source before this production engineering effort was estimated at 48 percent for the two diodes and 62.5 percent for the oscillators, which was raised to 90 percent for the GUNN diodes and 97.8 percent for the oscillators.

A new specification (SCS-412B, dated 3 March 1975) was generated which specified the electrical and environmental parameters to be met by the low cost X-band local oscillator. This new unit was tested for the first time to the relatively severe MIL-Spec environmental conditions similar to those required by the Ku-band oscillator. The X-band oscillator was shown to have met all of the specifications. No yield data are available. Figures 3 and 4 show the final design as adapted for use in portable radar, nearly 500 completed assemblies of which have been deployed.

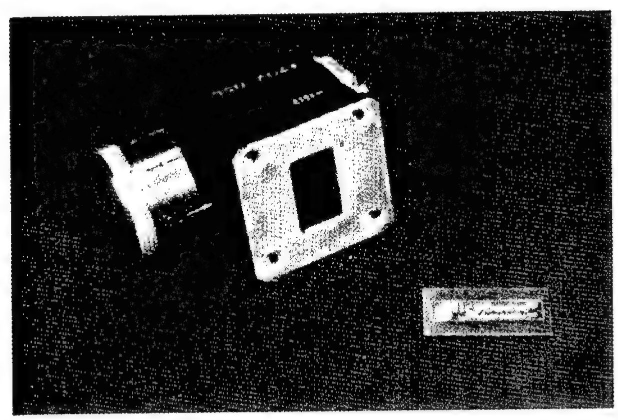


Figure 3

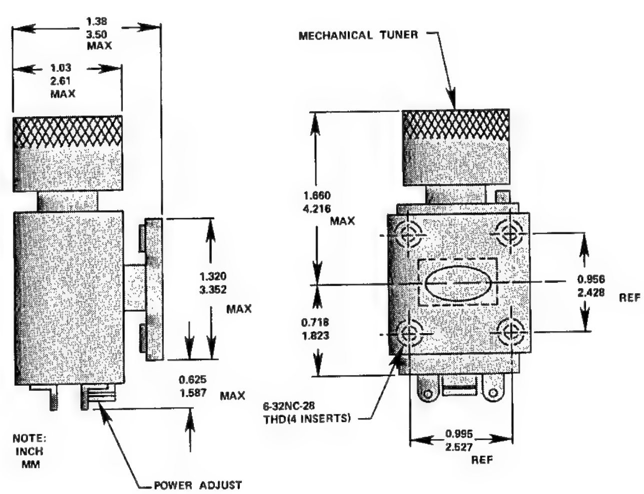


Figure 4

Crystal Units Meet Growing Need

Quantity Production by 1983

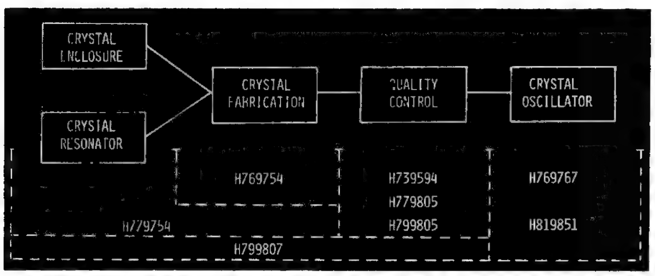
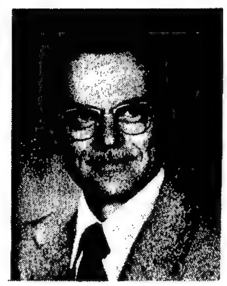


Figure 1



A native of Graz, Austria, DR. ERICH HAFNER received his Ph.D. in Physics and Mathematics from the University of Graz in 1952, where he was a Research Assistant in the Department of Theoretical Physics from 1951 to 1953. He came to the United States in 1953 to join the U. S. Army Signal Corps Laboratories (now ERADCOM) at Fort Monmouth, New Jersey. There, he conducted in-depth studies of and made contributions to nearly every aspect of quartz crystal resonators, precision oscillators, and atomic and molecular frequency standards. He is presently Supervisory Research Physicist engaged in research and development on frequency control devices for use in advanced communication and position location systems. Dr. Hafner is a Fellow of the IEEE and a member of the American Physical Society. He is Principal U. S. Member of Study Group 8 (Frequency Control Devices) of the NATO Group of Experts on Electronic/Electrical Parts and a Member of Study Group VII (Standard Frequency and Time Signals) of the International Radio Consultative Committee (CCIR). For the past five years he has been the General Chairman and Technical Program Committee Chairman of the Annual Frequency Control Symposium, an international meeting sponsored by the Electronics Technology and Devices Laboratory, ERADCOM.

Advanced military communication systems require high performance quartz crystal units and oscillators in quantities that cannot be provided by existing production techniques. Now, under a series of MM&T programs, the Electronics Research and Development Command (ERADCOM) is creating an entire new technology in crystal production techniques designed to meet these demands. The effort is aimed at automated production of a new flatpack enclosed design. Such units should lead to oscillator accuracies of 2×10^{-8}.

Figure 1 shows the thrust of the ERADCOM programs (designated by number) and their relationships. The overall effort now is well past the halfway mark and is on target toward meeting objectives. Quantity production of the new high performance devices should start in 1983.

Production Needs

Why is there such a need for improved crystal production technology?—First, consider the use of these parts. Quartz crystals and crystal oscillators are frequency control elements. Their major function is to provide signals at frequencies as nearly independent of environment and time as possible. In communications systems, they serve as reference oscillators for synthesizers and as rate generators for system clocks.

Stable frequencies are necessary, first of all, to keep radio transmissions on the assigned channel. Oscillator accuracy of between one and ten parts per million is generally adequate for this purpose. Advanced communications systems, however, are designed to use the same channel over and over again, both to accommodate more than one user on that channel and, particularly important for military applications, to provide secure, jam proof communications, navigation, and position location. This is done by assigning time slots or modulation codes—often a combination of the two.

Time Ordered Performance Higher

The use of time slots requires that participants in a given communications net have synchronized clocks. That in turn means that all clock rate generators—the oscillators—have to be at the same frequency during extended periods. Each one must be stable and accurate by itself. The degrees of stability required for the time keeping function are well beyond those necessary to simply keep the transmission on the assigned channel—by two to three orders of magnitude for systems in advanced development.

Although quartz crystal manufacture is a mature art, capabilities for large scale production have leveled off at just about the accuracy level needed to keep the transmissions on the assigned channels. Major innovations are required to satisfy the growing needs for time ordered systems with their much higher levels of performance.

More specifically, crystals currently produced for military use in large quantities have oscillator accuracies of about twenty parts per million. Commercial mobile radio equipment uses oscillators with accuracies between two and five parts per million. In contrast, the NAVSTAR global positioning system—one of the time ordered systems—requires oscillators with an accuracy of 2×10^{-8}, or 0.02 parts per million. The crystal/oscillator MM&T programs are designed to bridge this gap in large scale production capability in the near future.

Design Improvements

The first step in this effort was redesign of crystal units to allow automated production. Some typical quartz crystal units of traditional design are shown in Figure 2. Manufacture of such units requires more than thirty-two direct manual operations on the crystal resonator before the enclosures are sealed. This is a serious deterrent to quantity production of units with consistent high performance.

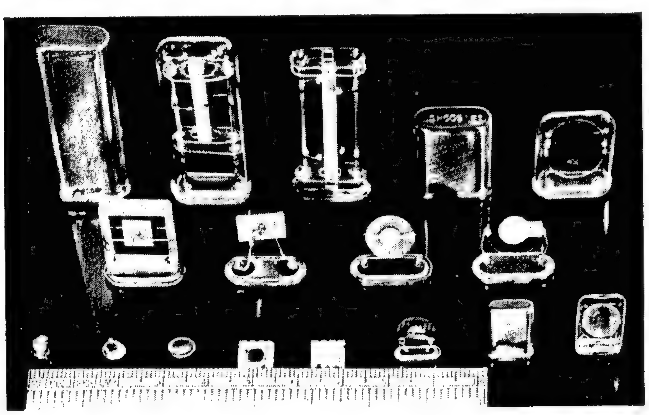


Figure 2

Components of the new flatpack enclosed design are shown in Figure 3. Assembled, they will look something like the crystal unit in the Tactical Miniature Oscillator shown in Fig. 4. The latter should enter its manufacturing engineering phase in FY-81. The flatpack design overcomes most objectionable aspects of the traditional crystal enclosures. In the flatpack, resonators are suspended by mounting clips inside the picture frame and the top and bottom lids are bonded to the frames by a thermal diffusion process involving electrodeposition of gold.

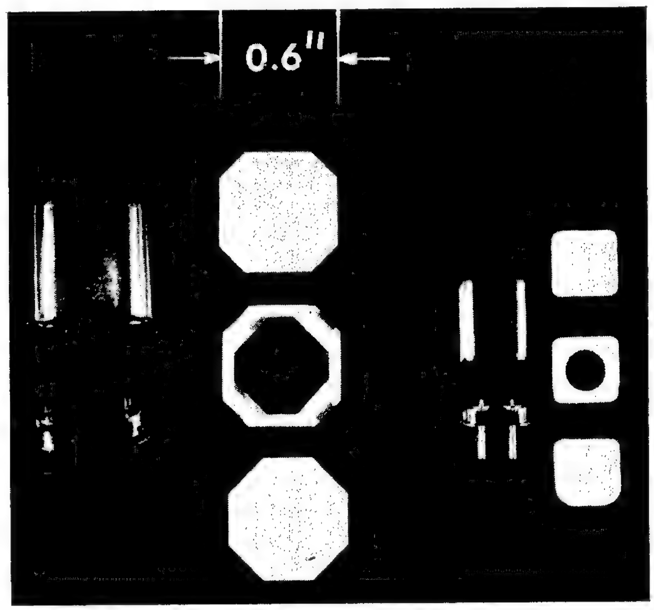


Figure 3

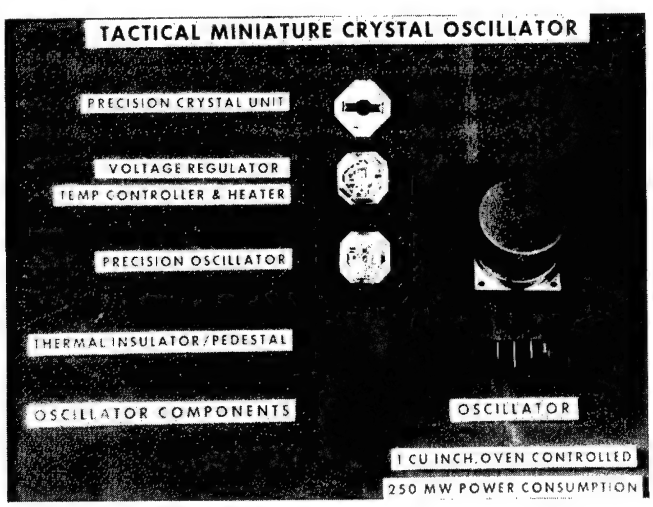


Figure 4

Production Methods

Taking this new design, the next step in the MM&T effort was to design equipment for quantity production. In the resulting manufacturing concept, the units will be assembled in quartz crystal fabrication facilities such as that illustrated in Figure 5. Figure 6 shows a facility of this type constructed at General Electric's Neutron Devices Division, viewed from the exit end. The inline arrangement of this facility provides for an automated, continuous cycle operation—no operator handles the crystal resonator during the cycle. Except for the entrance and exit chambers, all parts of the facility are under a continuous ultrahigh vacuum (10^{-8} torr). All system elements that require periodic servicing—for example, evaporation sources—can be withdrawn from the system through gate valves and serviced or replaced without affecting the vacuum in the chamber.

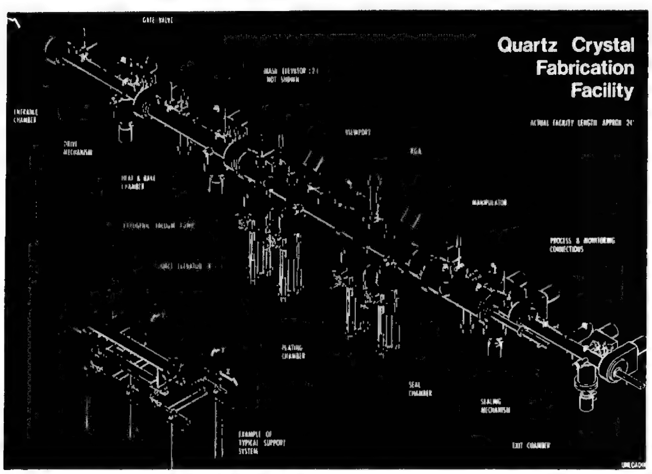


Figure 5

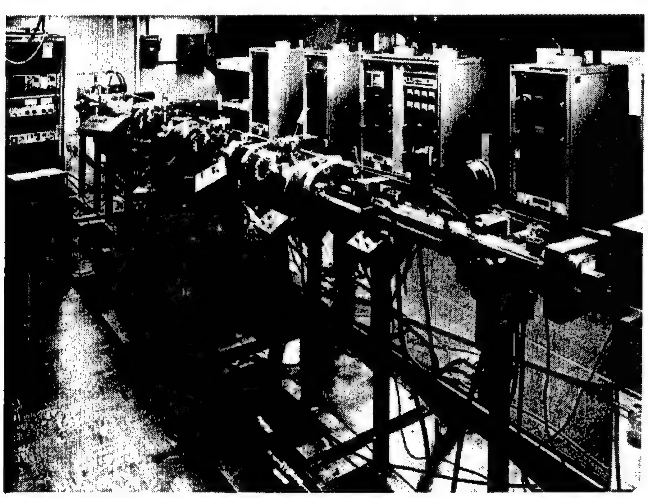


Figure 6

Process Sequence Depicted

Here, basically, is what happens in the manufacturing process as it is presently conceived. The flatpack components are stacked in a lid-frame-lid sequence on a special parts tray (Figure 7) with unplated resonators mounted in the flatpack frames. The trays hold stacks of up to twenty units.

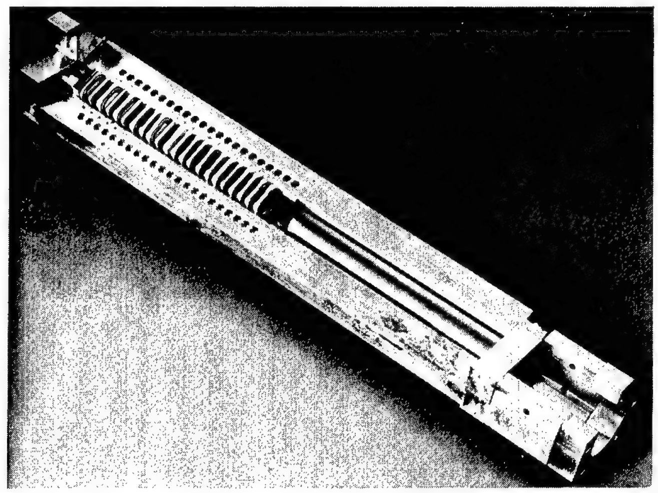


Figure 7

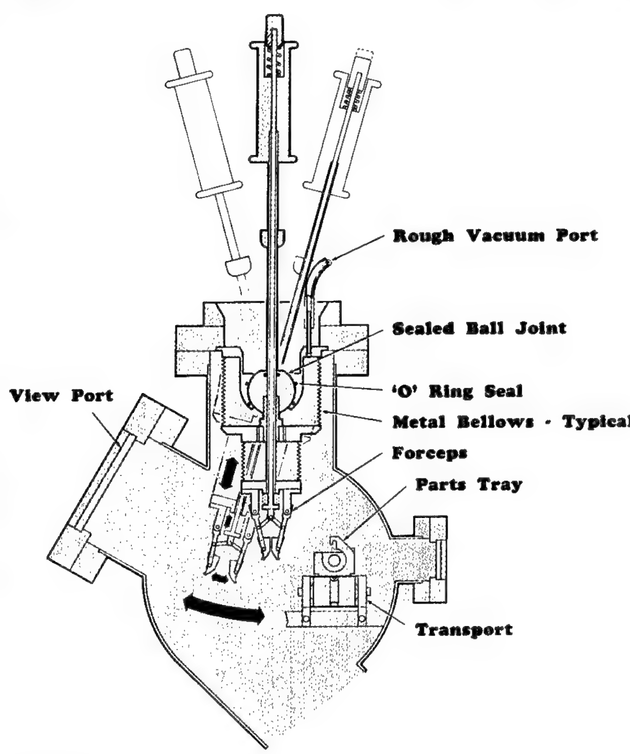


Figure 8

A vacuum manipulator (Figure 8) at the head end of the plating chamber picks up one frame at a time and inserts it into a mask head for electrode deposition. With the frame held vertically in the mask, four nozzle beam sources (Figure 9)—two each in the coarse and fine plating positions—deposit gold on each side of the quartz resonator. Gold not used in the columnated beam directed at the resonator recirculates through a large reservoir, permitting extended service between recharging operations. Following deposition, the frame is reinserted in the tray.

In the sealing chamber, the entire tray is picked up by a manipulator with a modified claw and placed into a sealing fixture. To seal the lids to the frame, the tray is heated to 320 C and the stack is compressed by action of a hydraulic ram against the pushrod seen in Figure 7.

Quality Assured Automatically

For quality control, a station like that shown in Figure 10 will be provided. Measurements on individual crystal units will be performed on the right hand station. Frequency/temperature and aging characteristics will be evaluated automatically in the temperature chambers to the rear on loads of 200 units at a time. An Electronically Tunable Microcircuit Admittance Bridge (Figure 11) will provide the interface between the crystal unit and the test instrumentation in both the single and multicrystal systems.

With full development of this design and manufacturing concept, quartz crystal production should be able to keep pace with the growing demands for high performance units.

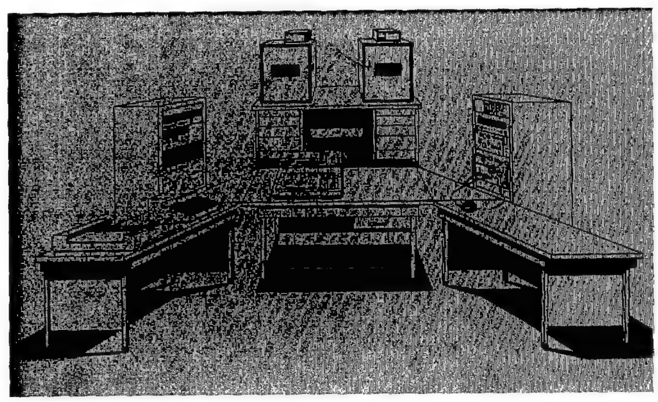


Figure 10

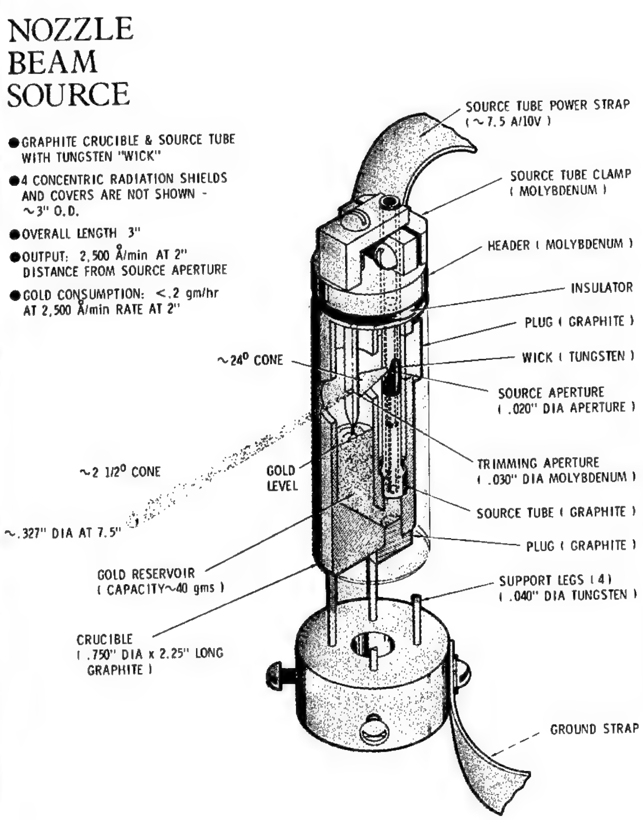


Figure 9

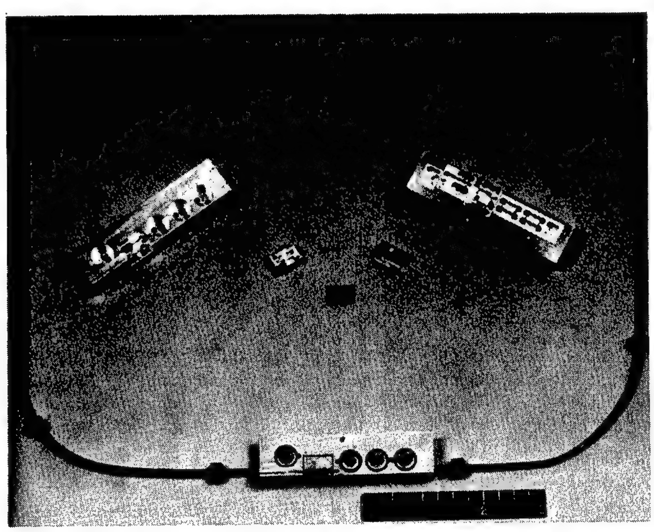


Figure 11

Avalanche Detector Modules In Production

Hybrids Replace Discrete Components

CLAIRE E. LOSCOE is an electronic engineer with the U. S. Army Communications Research & Development Command (CORADCOM) at Fort Monmouth, New Jersey, where she is project leader on R&D and MM&T programs for detectors and splice techniques for fiber optic links. Ms. Loscoe pioneered the development of the avalanche photodiode for Army Laser System applications shortly after the laser was invented in the early 1960's. She is the author of 22 papers and presentations. She received her M.S. degree, cum laude, from Fairleigh Dickinson University, Teaneck, N.J., and has pursued additional graduate work at New York University. She is a member of the Institute of Electronic and Electrical Engineers and the American Physical Society.

Small, rugged hybrid detector modules for two types of optical systems—laser rangefinders and fiber optic communications links—have been fabricated at production rates with costs significantly below those of previous discrete component assemblies. In a manufacturing technology program carried out by RCA, Ltd. of Canada for the U. S. Army Communications Research & Development Command (CORADCOM), this first implementation of production in lots of 100-500 reduced costs for fiber optic modules to approximately $660 per unit. In lots over 500, cost of rangefinder modules will be reduced to $200.

These detector modules are being used in the Army's AN/PVS-6 minilaser rangefinder and AN/TTC-39 switch and fiber optic communications link. The hybrid technology developed also is being used to produce commercial RCA components.

The performance of these modules (see Tables 1 and 2) exceeds specifications, providing small, rugged hybrid detector modules in production lots for the first time.

Basics the Same for Both Modules

The modules each contain three basic elements. The **rangefinder module** contains a silicon avalanche photodiode, preamplifier, and temperature sensor in a TO-8 package. The **fiber optic module** also contains a silicon avalanche photodiode and preamplifier, and in addition, incorporates a temperature compensating circuit which maintains the modules' responsivity in a changing ambient environment. The fiber optic module is fitted with a light pipe and connector for attaching an optical fiber.

Avalanche Detector

The rangefinder module utilizes the SCS-467, a fully depleted, "reach through" silicon avalanche photodiode that was developed by RCA, Ltd., Ste-Anne-de-Bellevue, Quebec, Canada, under a previous Army MM&T program. The fiber optic module contains a modified SCS-467, "etched well" device in which the depletion region has been reduced to half the thickness of the SCS-467. The thinner structure has sufficiently high quantum efficiency at the 0.82 um wavelength. It is operated, however, at a lower voltage (350v), which is necessary in order to utilize the temperature compensating unit (TCU). The TCU circuit maintains a constant value of avalanche multiplication by adjusting the voltage applied to the photodiode to compensate for changes in the temperature of the photodiode. The physical characteristics of the avalanche photodiode are shown in Table 3.

Rangefinder Module Performance		
	Specified	Typical Achieved
Responsivity	2.7×10^5 v/W	3.4×10^5 v/W
3db Bandwidth	20 MHz	29 MHz
Spectral Noise Density	5×10^{-8} v/Hz½	4×10^{-8} v/Hz½
Recovery Time	660 ns	580 ns
Power Consumption	75 mW	42 mW
Output Impedance	50 Ω	25 Ω

Table 1

Fiber Optic Module Performance		
	Specified	Typical Achieved
Responsivity	1.3×10^6 v/W	1.7×10^6 v/W
3db Bandwidth	16 MHz	22 MHz
Spectral Noise Density	5×10^{-8} v/Hz½	3.5×10^{-8} v/Hz½
Power Consumption	100 mW	38 mW
Output Impedance	50 Ω	25 Ω

Table 2

Preamplifier

Both modules utilize an unconditionally stable positive feedback preamplifier. Bipolar transistors instead of FET's are used in order to reduce recovery time and increase the maximum optical input the module can withstand. The avalanche photodiode preamplifier combination can survive a current surge of 14 amps without burn-

Photodiodes Used in Hybrid Integration
• **Rangefinder Module** Reach through avalanche photodiode (SCS 467) Chip thickness 120 μm Sensitive thickness 110 μm Wavelength optimization 1.06 μm
• **Fiber Optic Module** Reach through avalanche photodiode Chip thickness 120 μm Sensitive thickness 55 μm (etched well device) Wavelength optimization 0.82 μm

Table 3

ing out. Recovery occurs in 2 to 3 microseconds. Figure 1 shows the schematic for the rangefinder module. A temperature sensing diode is also included. Figure 2 shows the schematic for the fiber optic module; the diagram includes the temperature compensation unit.

Hybrid Circuit

The hybrid design is based on engineering models developed and fabricated earlier for the AN/GVS-5, the Army's hand held laser rangefinder. Both module assemblies consist of thick film resistors and conductors on an alumina ceramic substrate. Discrete RF transistors and temperature sensing diodes are attached to the mounting pads on the substrate with conductive epoxy. Solder reflow of ceramic substrate to the header pins, chip capacitors, load resistor Rl, and the pedestal for elevating the photodiode provides good mechanical attachment. The avalanche photodiode is soldered to a molybdenum tab which provides electrical contact and mechanical support. The tab, in turn, is attached to the pedestal with conductive epoxy.

Circuits Detailed

The rangefinder module circuit assembly is encased in a TO-8 package. The windowed cover is welded to the package to form a hermetic seal. The completed rangefinder module is shown on the left hand side of Figure 3. The fiber optic module circuit package is one inch in diameter and the windowed cover is replaced with a light pipe assembly. The completed module is shown on the right hand side of Figure 3.

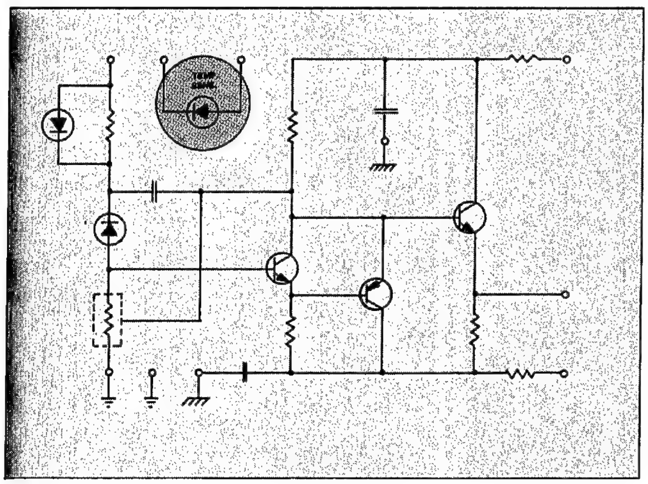


Figure 1

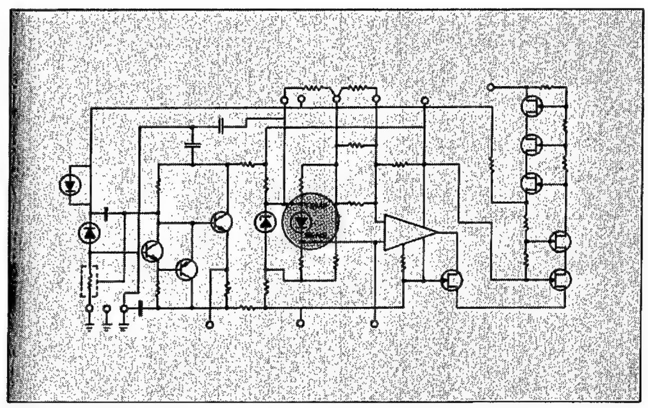


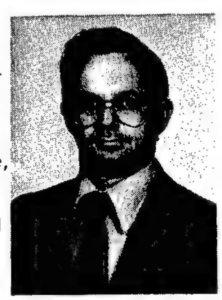
Figure 2

Figure 3

Continuous Drill Wear Monitoring

Infrared Sensing During Drilling

DAVID K. RUPPE is presently employed with the U. S. Army Communications Research and Development Command in the Automation Management Office. Mr. Ruppe's educational background includes a B.S. in Physics from Monmouth College in 1966 and an M.S. in Computer Science in 1972 from Fairleigh Dickinson College, also studies in Electronic Engineering. He has presented numerous papers and articles in the field of CAD/CAM since the early 1970s and has been an active advocate and participant in the development of automation for the design and manufacture of communications/electronics equipment.



Researchers at Hughes Aircraft have developed two temperature sensing techniques for monitoring drill wear that could solve a major problem in the production of multilayer circuit boards for military electronics systems. Although some modification may be needed for full-scale production use, the feasibility of the technology has been amply demonstrated.

Multilayer boards require the drilling of plated through holes. This operation has been constantly plagued by the occurrence of epoxy smearing over the hole sidewalls as the drills wear. Such smearing degrades electrical contact and can cause system failures. The expense of electronic systems and the requirements for high reliability demand that some means be found to overcome this problem.

Smearing Related to Drill Temperature

Hughes found positive correlation between epoxy smearing and drill temperature—as drill temperature increases so does the degree of epoxy smearing. The infrared sensing systems Hughes has developed to monitor temperature (both systems cost less than $5,000) can trigger the shutdown of a drilling machine when a predetermined drill temperature is reached. That temperature should be based on extensive observations of the relationship between epoxy smearing and drill temperature.

The Hughes effort, under the guidance of Principal Investigator Jack Quintana, was conducted under an MM&T contract with the U. S. Army Electronics Command. The objective was to develop a technique for continuous monitoring of drills in order to determine the point at which drills start to dull and epoxy smearing starts to develop.

Many Techniques Considered

Initially, Hughes evaluated various techniques of detecting drill wear. These included measurement of dimensional changes in the drill point, measurement of changes in drill motor performance (e.g., torque, drill entry force, feed rate), and temperature monitoring of either the holes or the drill. Measuring dimensional or mechanical variations was found to be impractical for a production application. For thermal sensing, the use of thermocouples, thermistors, or temperature sensitive paints was also ruled out from a production standpoint, although these techniques would have been fine for laboratory use.

Finally, two infrared sensing techniques (illustrated in Figures 1 and 2) were evaluated. The infrared radiation scope in Figure 1 views the drill with a close focus lens as it exits the hole and measures the infrared energy emitted by

the drill during operation. The output signal from the detector is displayed on a millivolt scale and can be recorded and converted to a temperature reading. The fiber optic device in Figure 2 also measures IR energy of the drill, using the fiber optics to transmit that energy to a remote detector. Again, the detector output signal can be displayed, recorded, and converted to a temperature reading.

Temperature/Smearing Relationship Established

In initial tests with these systems, drill temperature was monitored during drilling of a 4200 hole test pattern. The holes were drilled at 50,000 rpm, 200 ipm using the setup shown in Figure 3. Here, the multilayer board panel is sandwiched between an aluminum clad backup board and a 5 mil thick aluminum entry foil. Hughes has used this setup in production for several years to produce high quality holes.

The results of these tests showed that drill temperature increased steadily as more holes were drilled. This is illustrated in Figure 4. The boards were microsectioned and every 500th hole was examined with a scanning electron microscope for evidence of smearing. Epoxy smearing was first evidenced at 240-280 F in some panels and at 320-340 F in others. These were classified as Group A and Group B panels. Table 1 summarizes results of the calculations. The difference between the groups was attributed to some chemical or physical variation in the drills, since close control was maintained on the panels.

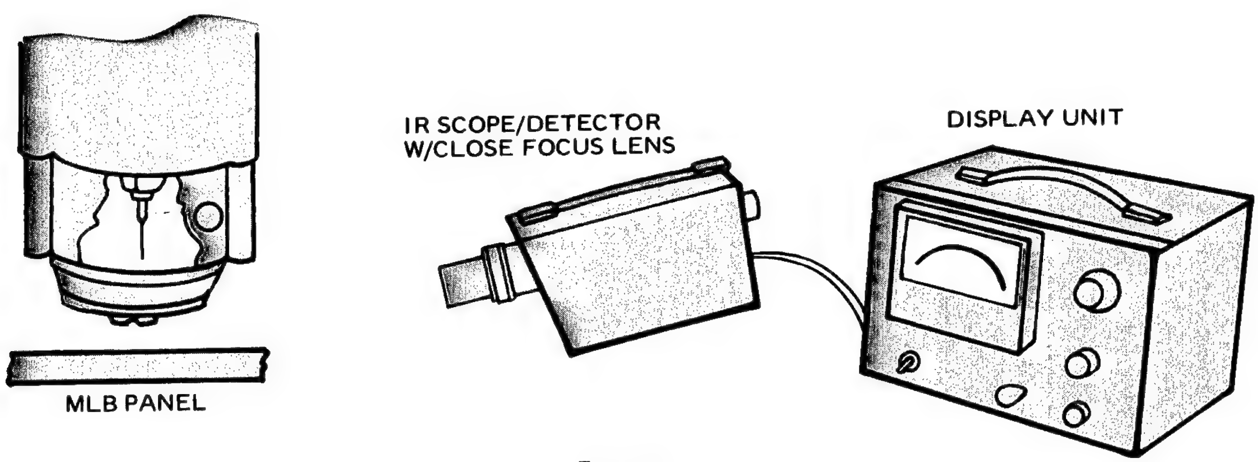


Figure 1

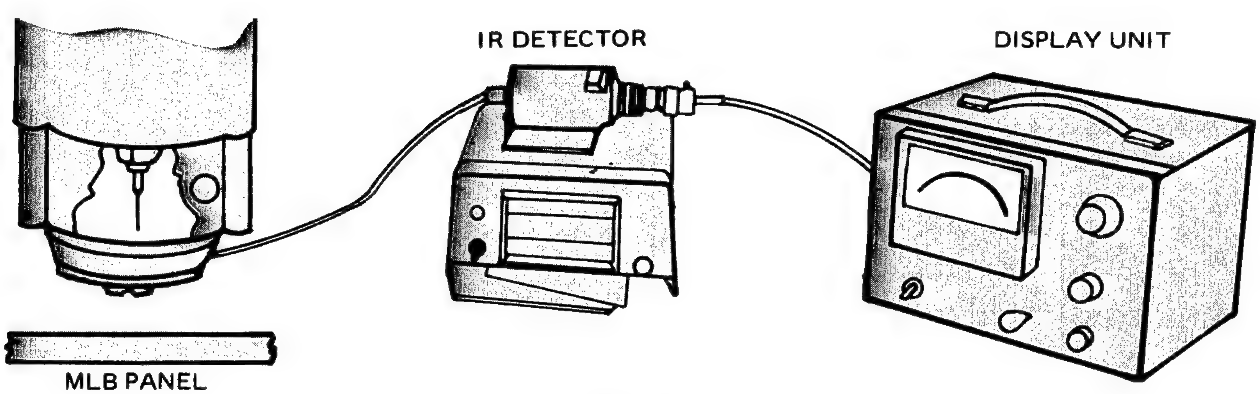


Figure 2

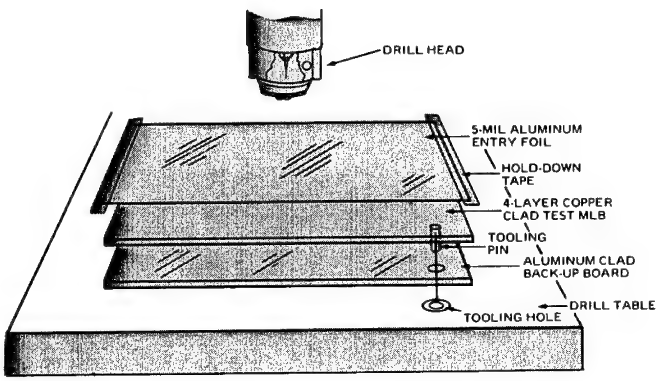


Figure 3

Drill Finish and Geometry Studied

The two sensors were also used to evaluate fourteen variations of drill finish and point geometry during drilling of approximately 3,500 holes. The results showed that drill temperature was higher for standard finish than for microfinish drills; that a microlube coating neither improved hole quality nor lowered the drill temperature; and that drill point geometry made no significant difference in drill temperature or hole quality.

Microfinish Drills Superior

Finally, temperature measurements were taken for drills of four sizes with both standard finishes and microfinishes. Holes were drilled at both 50,000 and 80,000 rpm.

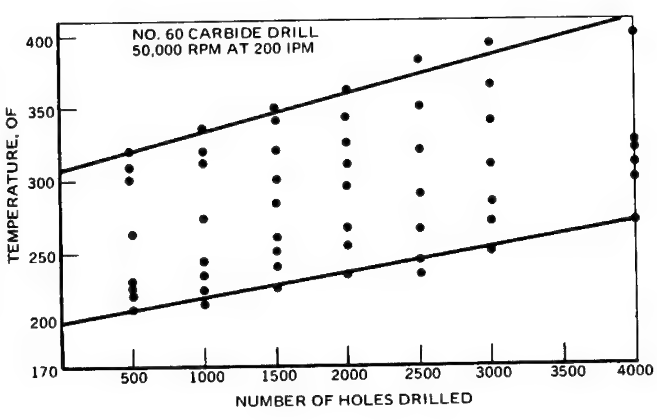


Figure 4

The amount of epoxy smearing on these holes was measured, assigned a numerical value according to a Hughes developed method, and compared with temperature readings. Observation of the resulting graphs indicated that

- As drill temperature rises, the amount of smear increases for each drill size, but the characteristics of the increase are different for each size.
- Drills run at 80,000 rpm show consistently higher temperatures than those run at 50,000 rpm (for all sizes) and the resultant smear value is also significantly higher.
- Larger drills run hotter, consequently the amount of epoxy smear is greater.
- Microfinish drills run cooler and produce less smearing, presumably because of reduced friction. The differences are less pronounced at 80,000 rpm.

As a result of the evaluation, Hughes recommended that microfinish drills be used for drilling multilayer boards.

No. of Drills Evaluated	Bad Hole/Smear Failures	Temp Of Drill At Failure	No. Of MLBs Drilled	Total No. Of Holes
14 each Group A	None at 500th hole 1 at 1000th hole 6 at 1500th hole 7 at 2000th hole	1 at 240°F 1 at 260°F 2 at 265°F 7 at 270°F 1 at 275°F 2 at 280°F	28	62,000
6 each Group B	None at 500th hole 4 at 1000th hole 2 at 1500th hole	1 at 320°F 3 at 330°F 1 at 335°F 1 at 340°F	12	26,000

Table 1

Production Use Feasible

Both the IR radiation scope and the fiber optics thermal monitor provide inexpensive methods for in-process monitoring of drill wear. Either could be used to automatically shut down a drilling operation at a predetermined drill temperature. Their use could provide a solution to the nagging problem of epoxy smearing in these multilayer boards.

To make such a system more suitable to production use, Hughes has made two recommendations:

- Curves for smear factor versus drill temperature should be developed for each drill type, size, and condition.
- The IR sensor should be modified by improving the temperature response and using filters to prevent light interference in order to reduce scatter in smear factor curves.

Quicker Inspection, Less Cost

Laser Scans of PC Boards

ROBERT L. BROWN is a General Engineer at the U. S. Army Missile Command in Huntsville, Alabama. His current projects involve creative direction of contractor engineers on projects such as the fully additive manufacture of printed wiring boards (Hughes), ultraviolet curing of conformal coatings for PC boards (Hughes), product cleanliness techniques for PC boards (Martin-Marietta), laser scan testing of PC boards (Chrysler), rigidflex assemblies (McDonnell-Douglas), and insertion of nonaxial lead devices in locaserts (Martin-Marietta), a recent approved success. A Registered Professional Engineer in Alabama and holder of a B.S. in Metallurgy (1958) from Alabama University, Mr. Brown holds six patents and is author of fifteen technical briefs which NASA rates as equivalencies to patents. He was the first recipient of the NASA "Noteworthy Contribution" award in 1970 for his many contributions to their technical utilization program, and patented several inventions that were used in production. While employed by Chicago Bridge and Iron in 1948 he invented an early television X-ray imaging system, which was the first such system to reach broadcast resolution and was the basis of an X-ray television system built by Zenith Corp. and delivered to Marshall Space Flight Center in 1972. This system was used at Vanderbilt University as the best available nuclear medical imaging system and is still in use there as a television X-ray system. His most recent development of an X-ray imaging system is characterized by revolutionary increases in resolution and performance through use of fiber optic technology, in which 80-100% of the radiation is captured in the image and resolution is more than 20 lines per inch, with increases easily possible through use of finer fibers. Also while at Chicago Bridge and Iron he patented a method for brazing claddings on dissimilar metals which was widely used commercially for many years. A member of the International Society of Microelectronics, Mr. Brown worked as an aeronautical engineer during World War II at Birmingham and also worked as an engineer with the Birmingham Fabrication Company.

Tedious manual inspection procedures that have been a bottleneck during automated high volume production of printed circuit boards no longer are required. Now, using laser scanning techniques developed during a manufacturing technology project for the U. S. Army Missile Research and Development Command, Chrysler Corporation's Huntsville Electronics Division automatically inspects these boards during manufacture. The process eliminates time consuming manual inspections, significantly decreasing inspection costs. For example, direct labor savings on annual production of more than one million boards for the Custom Analog Spark Control Computer (CASCC) total nearly 30,000 hours.

Another benefit of the laser scanning inspection system is greater reliability. With automatic in line inspection, discrepancies are caught prior to soldering, significantly decreasing repair costs. In addition, the microprocessor used with the scanner can alert operators to frequently occurring faults and allow early correction of malfunctioning equipment.

Automated or Manual Scanning

Basic components of Chrysler's Inspection Scanner are shown in the block diagram (Figure 1). The x-y galvanometer directs a focused laser beam onto the printed circuit board while photosensors measure the reflected energy from the board. The microcomputer controls the inspection by retaining data banks of circuit board parameters, generating laser scan patterns for fault detection, and monitoring the photosensor electronic output to make pass fail decisions. The working system is somewhat more complex than this basic model, requiring mirrors to cover a complete board and multiple photosensors to optimize fault detection capability.

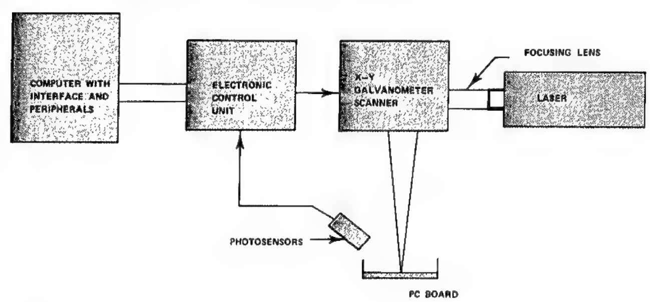


Figure 1

Chrysler uses the Inspection Scanner at two points in the manufacturing process:

- Following automatic insertion of the PC board prior to soldering to ensure that all components are in place and that all leads are clinched in the proper direction and of proper length.

- Following wave soldering to detect solder bridge defects.

The Chrysler system is applicable to boards as large as five by ten inches. Equipment can either be mounted as a station on a conveyor in a fully automated operation or used as a desk top unit for manual feeding of boards.

Shadows Tell the Story —color

To detect component presence and lead direction and length, the photosensors are set at a 45 degree angle to the plane of the circuit board so that the component lead blocks the laser beam's reflection, preventing it from

reaching the photosensor. This is illustrated in Figures 2 and 3. Two photosensors are required, one above the board at 45 degrees to detect near horizontal leads and one at the side of the board—still at 45 degrees—to detect near vertical leads.

The optimum scan pattern for component inspection is a 90 degree arc with a radius slightly larger than that of the lead hole. This arc is scanned in four equal segments. As shown in Figure 4, if a properly clinched component lead is scanned, a highly detectable null is seen on the photosensor wave form. When the lead is too short or is clinched in the wrong direction (or when the component is missing), the null signal does not occur and the board is rejected. Leads that are too long can be detected by repeating the scan with an arc radius slightly larger than the maximum allowable lead length. Here, a null in the wave form indicates the lead is too long.

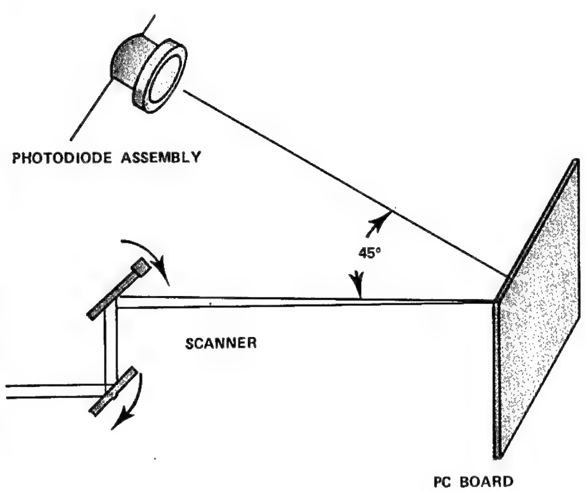


Figure 2

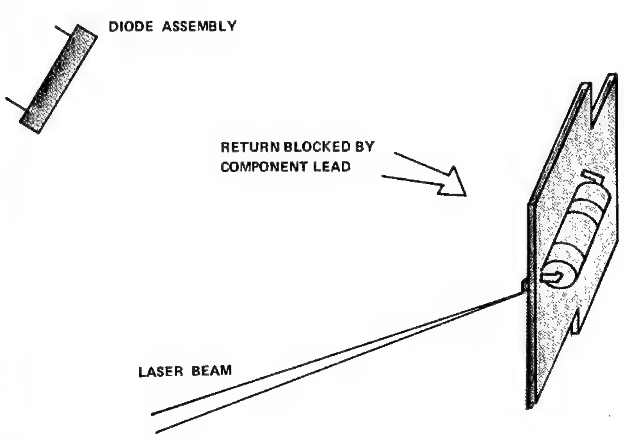


Figure 3

Over 100 Scans/Second

The average scan time per lead is 11 to 12 milliseconds. Thus, the CASCC computer board referred to previously—which has approximately 400 leads—can be inspected for

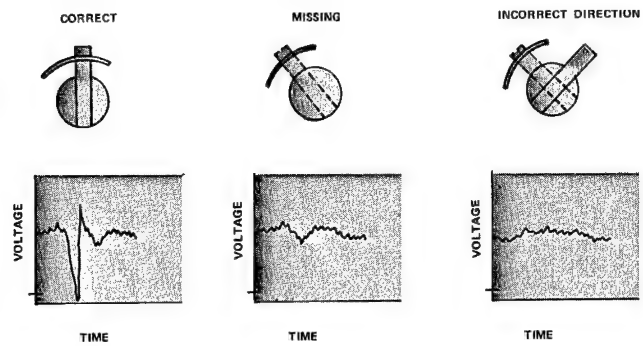


Figure 4

component presence and lead clinch direction and length in about 4.5 seconds. When this time is compared with that required for manual inspection procedures previously used, the annual savings for production of 1,093,000 boards totals 12,057 hours. (Note, however, that the initial setup to program the scanner requires about five seconds per lead, including debug time, so the technique is not cost effective for small scale production. Time study estimates indicate that a production rate of less than 10,000/ month is not economical.

Another possible inspection at this point in the manufacturing process would be to determine not only if components are present but if they are the **proper components.** However, Chrysler's investigation showed that the Inspection Scanner is neither practical nor cost effective for this application. There is simply too much variation in size, shape, and marking of components on any one board.

Post Soldering Inspection Pays Off

One special place where the technique is highly reliable and cost effective is in post soldering inspection (Figure 5), where labor savings are even higher than for component and lead inspection. There are numerous possible defects that may result from wave soldering—lead relief, excessive solder, insufficient solder, dewetting, cold solder joints, lifted foil, bridges, icicles, and unseated components. Chrysler undertook extensive experimenta-

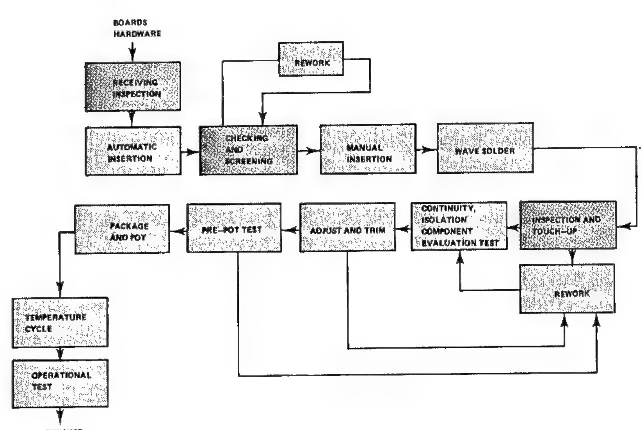


Figure 5

tion and analysis to determine which of these defects could be reliably and automatically determined by laser scanning. They found that, in most cases, considerable software development would be required and the procedure probably would not be cost effective. However, solder bridges, one of the most prevalent defects, can be readily detected by laser scanning, eliminating a time consuming manual inspection step.

17¢ Saved Per Board

To detect solder bridges, the laser beam scans a line segment between each of the pads on a board where this defect may occur. Reflective light again is monitored by a photosensor. The angle of the photosensor to the board is such that when the beam encounters a solder bridge, reflection to the sensor is blocked, causing a null signal. Using this technique, solder bridges as low as 0.020 inch can be detected.

Scanning time for this inspection is about seven milliseconds per line. The entire CASCC board can be scanned for solder bridges in about two seconds. This represents a savings of 53 seconds per board over manual inspection, or 17,306 hours per year. For a similar board and at a $10 per hour costing rate, these savings would pay for a computer and scanner (about $36,000) after inspection of about 220,000 boards. Programming for scan locations to detect solder bridges is much simpler than for component and lead clinch inspection, requiring only about one fourth the setup time.

Some Possible Applications Impractical

A simplified version of the laser scanner also can be used to detect icicles as small as 0.015 inch in diameter. (Icicles are formed when solder solidifies prematurely and stretches into a long, thin, wire like spur extending above the board surface.) In this case, a collimated laser beam is directed across a conveyor belt to a photosensor slightly above the conveyorized circuit board. Chrysler has not found this application to be cost effective, however.

Chrysler also investigated automatic inspection of incoming boards, but determined it would not be cost effective since quality is already quite high and random inspection is adequate. They also determined that the technique would offer no particular advantages or savings during vendor board manufacturing operations.

CRT Screen Provides Instructions

A schematic of the Inspection Scanner is shown in Figure 6. The microcomputer for the Inspection Scanner can control several independent scanner heads simultaneously, with the number depending on the board inspection rate. The computer subsystem includes a magnetic tape reader to load scan routines, diagnostic software for troubleshooting, and data banks for circuit board configuration. There is also a cathode ray tube viewer with keyboard to generate date banks and digital/analog converters and discrete input and discrete output cards needed to control the scanner patterns, monitor photosensor status, and provide the pass-fail decisions.

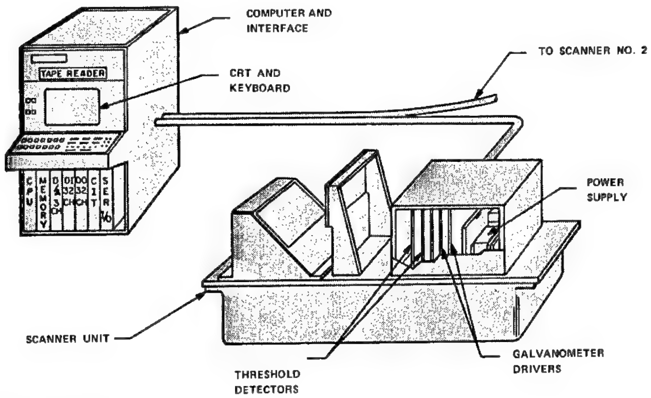


Figure 6

The microprocessor designates the failure locations and alerts the operator when the same failure is repeated excessively. It also can be set up to stop the production line in the case of repeated failures of the same type.

Sturdy Structure for Stability

The scanner head includes a mounting plate with all scanning components rigidly attached, a cast protective cover over the optics, a cast cover with window and receiving mirrors, and a scan electronics package. A post-objective scan lens and scanner arrangement is used—i.e., the galvanometer scanner follows the lens. In operation, the helium-neon laser output beam is expanded by a short focal length negative lens, then focused by a positive lens after being turned 90 degrees. Next, the converging beam is pointed by a general scanning x-y assembly. At this point, the beam is split into one of two identical paths by a mirror mounted on a rotary solenoid; this is done to provide scanning over a five by ten inch circuit board by scanning two five by five inch sections with small scan angles. Each displaced beam then is directed 90 degrees by a precisely adjustable mirror. Finally, the path is reflected by a fixed mirror 90 degrees to focus the beam on the circuit board.

Least Expensive Configuration Works

Four identical photodetector modules receive scattered energy from each five by five inch section of the board. Each high gain detector module is illuminated by a fixed vertical mirror and an adjustable mirror. The x and y axis receivers are designed for nominal 45 degree scatter angles. There is an alternative preobjective configuration for the scanner which can eliminate field curvature (allowing a wider angular range to reduce nonrepeatable errors) and provide telecentric operation (which eliminates effects of z-axis spacing on scan accuracy). However, the lens for this system costs $1000 to $6000, compared with $15 to $20 for the lens on the postobjective scanner.

Furthermore, absolute accuracy is not needed in the present applications, and field curvature problems can be solved by using a long focal length lens to maintain the desired spot size (less than 0.005 inch) over the image field. Thus, the postobjective configuration is quite adequate for the printed circuit board application and costs much less than the alternate configuration.

Less Machining = $ Savings

New Process Forms Small Arms Parts

JOHN JUGENHEIMER is an Industrial Engineer for the Industrial Facilities Planning Branch at Rock Island Arsenal, where he presently is working on an MM&T program concerning induction heating for hot winding recoil springs. He also is actively managing a program to rebuild or replace the fifty-four overhead cranes used at the Arsenal. Prior to these tasks, he has led projects on the fine blanking of small caliber weapon parts (see accompanying article) and projects, also, on inertial welding, high energy forging, and the automated rotary forging of small caliber gun barrels. He has worked at Rock Island Arsenal since receiving his B.S. in Engineering Operations in 1965 and his M.B.A. in 1966.

Rock Island Arsenal has demonstrated the feasibility of fine blanking of parts for small caliber weapons at cost savings ranging from $0.96 to $6.91 per part. These savings, representing reductions in cost up to 45 percent, were achieved on seven parts of varying size, shape, thickness, and material by producing dies and fabricating sample parts. In addition, costs were estimated for ten other parts that appear suitable for fine blanking. The estimated savings for those additional parts ranged from $1.05 to $16.15, with reductions as high as 77 percent.

Cleaner Punching Technique

Fine blanking is a metal stamping process that produces parts with edges and holes fully shaved through the entire part thickness while holding very close part tolerances. It also can produce holes and webs less than part thickness. The primary savings arise through elimination of a large amount of the machining that normally follows conventional metal stamping operations.

In the conventional process, as shown in Figure 1, a punch pushes the part out of the feedstock through a hole in the die. This produces a bent part with much of the edge surface broken away, which then requires considerable finishing.

In fine blanking, the feedstock is held between the top and bottom dies by a v-groove, as shown in Figure 2. This keeps the stock flat and prevents the material from pulling in toward the punch. As the punch pushes the part out of the feedstock, a lower "punch" applies a counter pressure. This keeps the part flat while it is extruded through the die. The result is a smooth edged part that requires little machining.

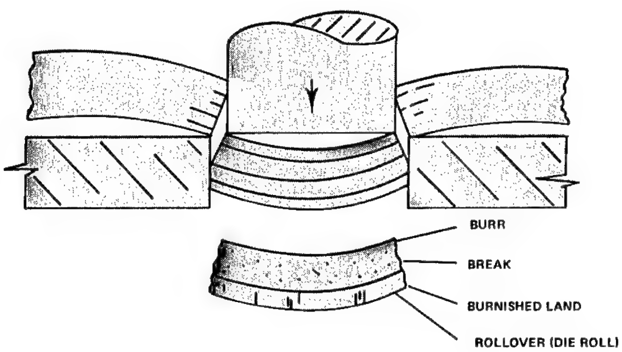


Figure 1

Higher Alloys A Target

The investigation at Rock Island was designed to determine the feasibility of fine blanking small caliber weapon components to close tolerances in higher alloy metals. The following parts were successfully fabricated at significant cost savings:

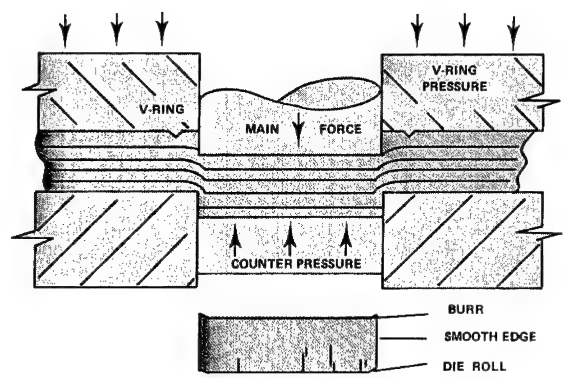


Figure 2

- **Trigger Guard.** The trigger guard was blanked from 1065 steel 5/64 inch thick to a finished outside contour with all required holes. The fine blanked preform needed only bending and finishing operations. Estimated cost savings were $3.10 per unit.
- **Hammer.** Blanked from ¼ inch 4150 steel annealed to Rb90 maximum, the hammer was successfully produced with only an occasional small tear on the front corner. Finish machining can remove these tears and allow use of this part as blanked with estimated cost savings of $6.91 per part.
- **Spacer.** The spacer was blanked from 3/16 inch 1019 or 1022 steel with excellent results at a savings of $0.96 per piece.
- **Washer, Key, Bearing Retainer.** This washer was successfully blanked from 1/8 inch 1018 or 1022 steel. The resulting parts were used in a production order. No cost comparison is available in this case.
- **Washer, Flat.** This washer, 11¾ inches in diameter, was the largest part produced as a fine blanking. Parts blanked from 1/8 inch 1008 or 1010 steel were highly satisfactory and were used on a production order. Cost savings were $1.05 per part.

Design Changes Sometimes Needed

Two other parts were blanked with limited success, but the problems that were encountered can apparently be overcome in the design. A **cartridge guide pawl** was blanked from 3/8 inch 4140 steel annealed to Rb90 maximum. Fine blanked pawls had a high percentage of tears on all four corners that made the blanks unusable. A redesign of the dies to allow additional stock on the corners would probably allow successful blanking with only a small amount of additional machining. Estimated cost savings of the redesigned part are $1.47. When a **cartridge link stripper** was blanked from 1/4 inch 8620 steel annealed to Rb90 maximum, a small amount of corner tearing resulted. Finish machining would remove most of these tears. Other corner areas would require additional stock to allow for machining cleanup. This part should also be blanked from thicker stock in a redesigned die. Estimated cost reduction is $5.57 per part.

Finally, a **cartridge case retainer** blanked from 1/4 inch 4340 steel annealed to Rb90 maximum showed frequent tears on all corners and on the long sides. The maximum tear depth observed was 0.025 inch. Metallurgical examination and hardness tests indicated that while tears increase as hardness increases, there are other factors that influence part tearing. It is felt that the small radius configuration of this part also contributed to the tearing problem.

Harder Materials Tear More

The Rock Island Arsenal investigation shows that fine blanking is effective and economical for use with high carbon steels, provided the metal is spheroidized annealed and of the proper hardness. The harder the material, the more likely it is that tears will occur in the blanked edge. Part configuration is also more critical with the high carbon alloy steels than with softer materials. A part with a sharp radius is much more likely to develop corner tears than one with a more gentle contour. Blanking of higher alloy materials also may reduce die life by up to 50 percent. The study showed that, for the process to be economical, large production quantities are required to justify the cost of equipment and tooling.

Dollar Savings Firm

As noted, engineering estimates of cost savings for ten additional parts suitable for fine blanking were prepared. Cost savings for both groups of parts are summarized in Table 1. The average estimated tooling cost for these parts is $7,922 per die set. As shown, the average cost savings per part produced is $5.19.

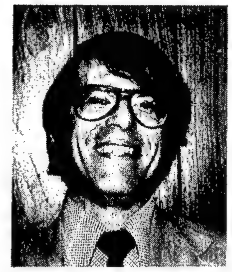
Using an equipment cost of $490,000 for a 440 ton capacity fine blanking press and the average part savings of $5.19, the breakeven point on cost would be at 94,412 parts. A five year payback of equipment costs therefore would require an annual production of 18,883 parts. In addition, more than 1500 units of each part would be required to pay back the tooling cost. Where such production rates are available, fine blanking of various parts should prove cost effective.

Calculated Cost Savings			
Component	**Std Hrs/ Part Saved**	**Percent Savings**	**Dollar Savings**
Trigger guard	0.1033	—	$ 3.10
Pawl, cartridge, guide	0.079	25.0	1.47
Hammer	0.2304	42.1	6.91
Stripper, cartridge link	0.1857	44.8	5.57
Spacer	0.032	31.0	0.96
Washer, key, bearing retaining	—	—	—
Washer, flat	0.0350	12.0	1.05
Cam feed	0.3072	22.4	9.22
Retainer	0.4656	37.8	13.97
Ring, lock	0.0930	76.9	2.79
Lever, feed actuator	0.5383	52.1	16.15
Rack	0.5176	76.6	4.73
Pawl	0.0507	52.6	1.52
Disc	0.1219	74.5	3.66
Disc	0.0525	60.6	1.58
Average	**0.2009**	**46.8**	**$ 5.19**

Table 1

Process Functions Costed

Funding Requests Zeroed In

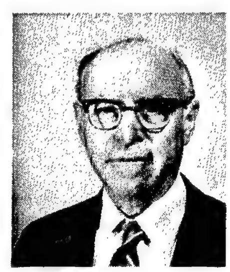


DR. ALLEN BAISUCK is President of Phoenix Data Systems, Inc., Albany, New York. Phoenix provides computer software products to assist digital logic circuit design and testing and also offers application and system programming services. Before this, Dr. Baisuck was Vice President and Division Manager of Management Systems for RRC International, Inc., of Latham, New York. During his tenure with RRC, he was Project Director of the U. S. Coast Guard sponsored study, ''Measures of Performance in Marine Environmental Protection'', the ''Health Professions Education Facility Survey'' conducted for the U. S. Health Resources Administration, and the ''End Item Manufacturing Guide'' for Watervliet Arsenal.

GENE R. SIMONS is Associate Professor and Coordinator for Quantitative Approaches to Decision Making at Rensselaer Polytechnic Institute. He has been a faculty member since he received his Ph.D. degree from RPI and has extensive teaching and business experience in production planning and control, work measurement, quality control and analytical methods. Earlier he was a staff industrial engineer for the American Cyanamid Co. Previously, he was a plant engineer with Western Electric. He has served as a consultant and has published articles on technological forecasting and systems evaluation. He is a senior member of the American Institute of Industrial Engineers.

Functional commonality of manufacturing processes—a technique similar to group technology classification—was the new approach developed at Watervliet Arsenal to pinpoint areas of high cost manufacturing. The data developed via this new concept is used in determining future funding requests by manufacturing engineers at Watervliet. These funding requests are aimed at improving production methods on the U. S. Army's heavy weapons manufactured at Watervliet.

Result of a study entitled ''A Technology Independent Method of Process Review'', the new technique describes current manufacturing processes in terms of the functions they perform, thus allowing assessment of costs without reference to the methods employed. Such ''technology independent'' assessment allows cost comparisons both within and among end items, thereby highlighting the high cost functions.



HAROLD GOODHEIM is a Project Engineer in the Advanced Engineering Section at Benet Weapons Laboratory, Watervliet Arsenal, N. Y. His duties include responsibility for coordinating manufacturing technology projects from their initiation to the funding stage for the Benet Laboratory. He also initiates and oversees mantech projects at Watervliet. Mr. Goodheim is a graduate of the Massachusetts Institute of Technology with a degree in Chemical Engineering. He also has pursued graduate courses in metallurgy, lubrication, and fracture mechanics at Rensselaer Polytechnic Institute and Union College. He currently is working to implement Group Technology at Watervliet Arsenal. Mr. Goodheim is a Professional Engineer licensed in the State of California, and he holds a patent for a process applied to extreme pressure lubrication of gun tubes. He is a member of the CAD/CAM Committee of MTAG (Manufacturing Technology Tri-Service Advisory Group) and a member of SME.

twenty strands of twenty end count prepreg roving on the torque tubes and trailing edge.

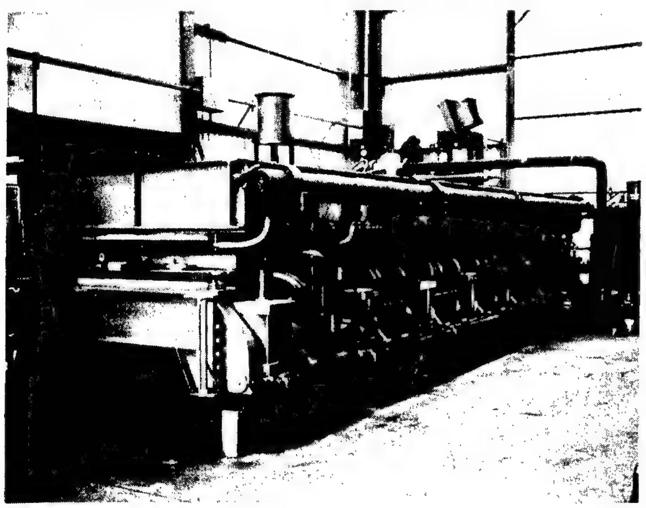
The inner and outer spars, the trailing edge, and the blade body assembly are bonded on an **integrally heated bonding press** manufactured by Thermal Equipment Corporation of Torrance, California (Figure 6). This four by thirty foot press weighs 106,000 pounds and can bond parts up to ten inches thick in only half the time of an autoclave. A unique temperature hold feature guarantees uniformity of heating for the entire unit or minus five degrees.

The press can cure components up to 400 F and also can preprogram rates for temperature rise and cooldown. Heat transfer is by direct contact with heated platens rather than convection by air as with an autoclave, making the press more energy efficient. Other advantages include less structure in basic bond tools, elimination of problems associated with envelope bagging, and the capability for visual inspection during the cure cycle.

A **filament compaction machine (Figure 7)** manufactured by L&F Industries in Huntington Park, California, compacts orbital filament wound parts to design shape, density, and cross sectional area. Spar straps initially were compacted using bars actuated by hand operated screw clamps. This required many man-hours, and the tools and clamps were damage prone. A prototype electrohydraulic powered station designed at Bell provided the basis for the production machine.

Other equipment and facilities that have been especially designed and installed for production of fiberglass main rotor blades include

- Overhead hoists to handle winding and bonding tools
- A heated table to warm winding and bonding tools and to facilitate compacting of parts
- A recirculating oven for bringing prepreg roving packages to room temperature for winding
- Fluoroscopic nondestructive evaluation equipment and a room equipped for handling the rotor blades during inspection
- Refrigerated raw material storage rooms for prepreg roving and adhesives
- Refrigerated storage rooms for wound prepreg components.



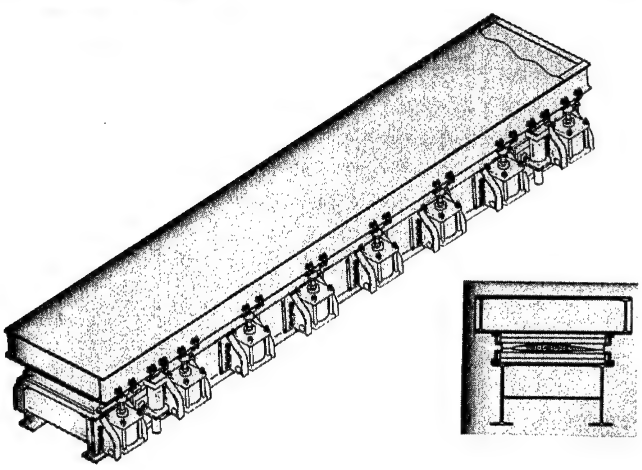
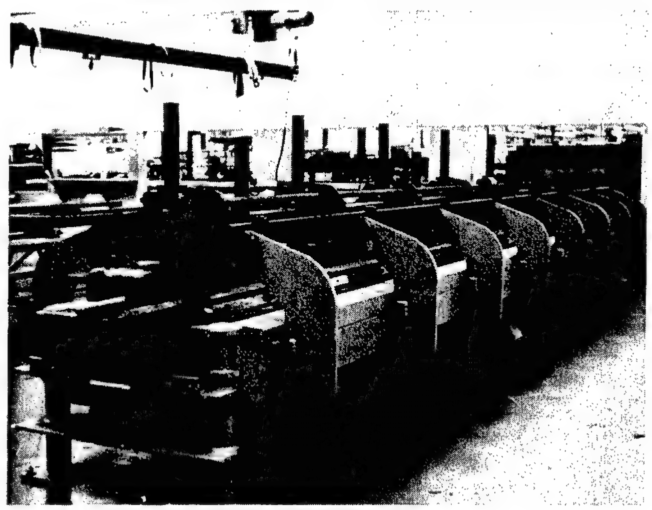


Figure 6



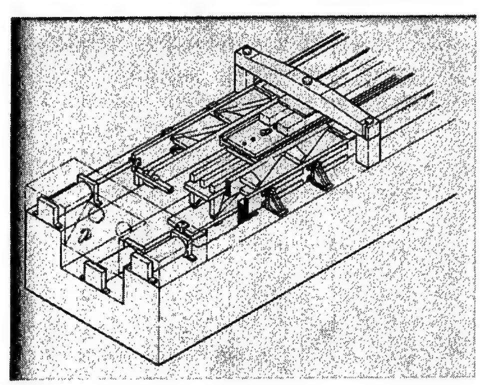


Figure 7

Based on available data, a Process Analysis Structure has been developed comprised of nine interrelated tables which are used by an analyst to search for new combinations of operations and to determine high cost production functions. This procedure, involving also a new method for indirect cost allocation, has been validated at Watervliet with actual data relating to production of large weapon systems.

Large Components, Close Tolerances

The study was conducted in 1974 at Watervliet Arsenal for the purpose of developing an End Item Manufacturing Guide. This guide was to be used principally to systematically identify areas where manufacturing methods could be improved to reduce the cost of manufacturing large weapons systems. The study was conducted by a multidisciplinary team consisting of personnel expert in computer systems, metals technology, management systems, and manufacturing technology. The large weapons systems manufactured by the Arsenal, ranging from the 81 mm mortar to the 175 mm cannon, present a number of unique problems in manufacture—primarily in trying to hold close tolerances on large metal pieces without changing their metallurgical structural characteristics. Machine tool investment is very high, while production volume (except during national emergencies) tends to be low. Under these constraints, the guide was established to assist in the following kinds of tasks:

- Development of specifications for new technology
- Evaluation of the feasibility of attaining high volume production mixes, such as mobilization quantities
- Cost and throughput comparison of alternative production methods
- Rate of return analysis
- Analysis of various end items' competition for processing resources.

Functional Classification Scheme Conceived

To accomplish such tasks, it was necessary that the implementation of the guide incorporate time and cost data in a rather unconventional way, primarily due to the desire to utilize current data in a manner precluding concentration on the details of current technology. The latter concern was accommodated through development of the concept of a "functional classification scheme" (FCS). By describing each current manufacturing activity or process in terms of the **function being performed,** it becomes possible to assess the current costs of performing the functions required to produce a given end item—without reference to the methods employed. By then comparing these "functional costs" both within and among end items, it was anticipated that high cost functions would be pointed up for further manufacturing research effort. Moreover, the technological independence of the functional approach would be helpful in the assessment of commonality among various end item manufacturing processes, competition for production resources, and new technology transferability.

True Costs Determined

A second major aspect of the approach was the development of a more truly representative method of indirect cost allocation. The Arsenal uses a step down standard costing system that accumulates cost based on organizational level rather than processing area. In brief, rather than assign the exact same indirect costing rate (as a function of direct labor hours) to all end items, a procedure was developed for assigning, in a **direct manner,** as many "indirect" costs as possible. This procedure proved most helpful in determining the true monetary value of a proposed manufacturing process improvement.

Operation Commonality Via FCS

The functional classification system (FCS) is similar in concept to the Group Technology classification systems in that it attempts to describe the product in general terms. The important difference, however, is that whereas the objective of Group Technology is to classify similar parts into families in order to improve machine utilization and reduce setup cost, the objective of the functional classification scheme is to identify commonality in operations on the same part (a 20 foot long gun tube forging, for example) in order to better group them on the several machines used to manufacture the part.

The FCS codes (see Figure 1) described the operation by

- Type—metal removal, metal forming, metal joining, metal treatment, measure/inspect
- Size—large, small, large/long
- Extent—major, minor, detail
- Purpose—cylindrical surface, planar, curved, complex, hole
- Character—rough, finish
- Other—interior, exterior, hollow, solid.

Functional Classification Scheme

	A. Metal Removal	B. Metal Forming	C. Metal Joining	D. Metal Treatment/ Finishing	E. Measurement/ Inspection
I. Size of item	1. Large, massive item 2. Large, long item 3. Small item	1. Large, massive item 2. Large, long item 3. Small item	1. Large, massive item 2. Large, long item 3. Small item	1. Large, massive item 2. Large, long term 3. Small item	1. Large, massive item 2. Large, long term 3. Small item
II. Extent of Operation	1. Major feature 2. Minor feature 3. Detail	1. Major feature 2. Minor feature 3. Detail	1. Major joint 2. Minor joint 3. Attach. joint	1. Total bulk 2. Localized bulk 3. Entire surface 4. Localized surface	1. Overall bulk 2. Localized bulk 3. Overall surface 4. Localized surface
III. Purpose of Operation	1. Cylindrical surface 2. Planar surface 3. Curved surface 4. Complex surface 5. Hole	1. Cylindrical shape 2. Planar shape 3. Curved shape 4. Complex shape 5. Hole/blank	1. Simple joint 2. Complex joint 3. Lin. ext. joint 4. Cylindrical joint	1. Modify material prop. 2. Modify texture 3. Apply/form film 4. Deposit metal. coating 5. Deposit nonmetal coat 6. Clean	1. Dimensions 2. Thickness 3. Contour 4. Profile 5. Conformation 6. Surface finish 7. Flaws 8. Mech. Properties 9. Physical Characteristics 10. Chemical composition
IV. Character of Operation	1. Rough 2. Finish	1. Rough 2. Finish	1. Load bearing 2. Non-load bearing 3. Sealing	1. Preliminary 2. Final	1. Preliminary 2. Final
V. Other	1. Interior of item 2. Exterior of item 3. Interior and exterior	1. Hollow item 2. Solid item	1. Thin section 2. Thick section 3. Very thick section	1. Interior of item 2. Exterior of item 3. Interior and exterior	1. Interior of item 2. Exterior of item 3. Interior and exterior

Figure 1

This coding, along with classification of the holding surface (surfaces in contact with the machine mounting) and the action surface (where the cut or bend was being made) were the main building blocks of the analysis scheme described below.

Study Procedure Developed

The study procedure consisted of six major steps:

(1) A functional classification scheme was developed to provide a generic definition for each of the processes used in the manufacturing of the end item.

(2) A "Process Analysis Structure" was developed by relating the **information** desired in the guide to the **data** required to be collected to produce such information.

(3) The available data sources were evaluated to determine their applicability in view of the data requirements derived in Step (2).

(4) A single end item was selected for validation purposes (the 105 mm M-68 tube).

(5) Data were gathered for the 105 mm M-68 tube.

(6) The process analysis of the 105 mm M-68 tube was conducted, thus validating the data gathering procedures and the value of the guide itself.

Analysis Procedure Designed

As a result of this study, an end-item analysis procedure was designed consisting of three steps:

Step 1: Gather required data on manufacturing process.

Obtain and Verify Documents. In our case, this involved route sheets, component travelers, engineering performance standards. Verification entailed cross checking among documents.

Develop Flow Process Chart from the Documents. A flow Process chart was used to check existence of operations and inspections and their sequence. Development

of the chart entailed on-site observation (in chronological order) of the process, the equipment, the move type, and the locatio.ı.

Fill Out Data Collection Form (see Figure 2). (1) Entries are from manufacturing documents readily available. Each operation is broken down into activities which are described, given the appropriate FCS code and function, and assigned proportionate times. Most of this work has already been done prior to the operation going out on the shop floor. Activities can be coded while times can be taken from performance standards and estimated times on route sheets to be apportioned among multiple activities. (2) Make a sketch of the end item and label the surfaces for identification. Code similar items in the same sequence. (3) Verify the data form by direct observation and talking to operators on the shop floor.

Step 2: Gather required data on indirect and direct labor costs and prepare rates.

Obtain the required documents, which at Watervliet Arsenal were:

- The budget worksheets—supplying manpower figures.
- The budget for the fiscal year under consideration.
- The distribution of machines by geographic, functional, and department assignment.
- The list of machines sequenced by WV (arsenal code) number, PEC (Army), type of facility, and location.
- Copies of the route sheets for each end item.
- The projected production quantities for the period and peak production quantities.

DATA COLLECTED

Item	Explanation
Operation Number/Activity	Breakdown Used on the Engineered Time Standards
Cost Area	Department Location of Operation
Description	Of the Activity ("Ream", "Mill", etc.)
Equipment Type	Code Number ("WV" No.) of Machine Used
Location	Building and Bay Number
Function Code	See Figure 1
Subsequent Move Type	Coded Move Type After Activity Completed
Hold Surfaces	Contact Surfaces With Chucks, Roller Rests, etc.
Action Surfaces	Where Is the Cut, Bend, Inspection Taking Place
Make Ready / Do / Takedown } Times	From Engineered Time Standards
Operation, No. of Facilitated or Corrected Operation	Facilitate (True Up, for example) or Correct (Straighten, for example)

Figure 2

Develop Cost Analysis Tables, which are in essence a reorganization of the data on manpower (direct and indirect) and an allocation of their costs to each activity by department.

Set Up A Data Analysis Sheet for Computerization. This analysis sheet contains the following items for each functional activity:

- Relates coded operations with Time and Cost.
- Work surfaces for each process.
- Coded move types (based on handling facility used).
- Equipment used in operations.
- Breakdown of direct and indirect labor costs and allocation of costs to each coded operation.

Step 3: Generate Analytical Reports. Some of the reports generated are:

Per Unit Function Cost by End Item. Shows the per end item cost of each function required to produce that item, given "today's" production process. As a result, it allows comparison of both the absolute and relative costs of performing each of the functions.

Labor Concentration by End Item Surface. Shows the time and effort, both direct and indirect, expended on each surface of the end item. This report is designed to give insight into those locations or surfaces of the end item that are more than proportionately expensive to process or produce.

Process Candidates for Combination. Aids the analyst in discovering and evaluating the time/cost benefits of combining production activities that are compatible with combination. In this report, compatibility is couched in terms of "similar functions, similar hold, and action surfaces". It is based on the assumption that two functions that take place on the same surface while the end item is being held in the same fashion are logical candidates for either sequential or simultaneous combination.

Per Unit Function Time vs Process. Correlates function and process descriptions by displaying the cost of each process embodied by each function. The report allows a cost comparison of performing a given function through different processes and may trigger attempts at technology transfer within the manufacturing cycle of a single end item or between end items.

Facilitating and Correcting Activities. A facilitating operation is one which supports (or corrects) other operations. This report indicates the source—and costs—of operations which are productive only in a limited sense and which should, if possible, be eliminated.

Production Mix Feasibility Analysis. Lists all the available machine tools and the processing demands to be made upon each at a given mix level. It allows assessment of (1) potential production bottlenecks of the mix in question; (2) substitutable equipment; and (3) the amount of additional equipment needed to satisfy the mix's requirement.

After the guide was designed, it was demonstrated on a single end item chosen by the Arsenal—the 105 mm M-68 gun tube. On this end item, which has 100 operations, the analysis reports showed the following:

	% of Total Time	% of Total Cost
Metal Removal	81.4	63.0
Forming	8.1	7.5
Treat/Finish	3.6	4.5
Measure/Inspect	6.9	25.0

Review Team Poses Questions

The Arsenal review team consists of engineering support personnel with manufacturing experience, such as machining technicians, engineers, and management personnel, including group and section leaders. The review team first discusses the reports in general terms with management. Then the working group of technicians and engineers dig into the reports covering areas selected by the review team for intensive study. From this detailed study emerge recommendations for specific projects.

For example, the review team in one session came up with these points for further study. From an adaptation of Report No. 1, which linked the route sheet operation numbers and activity descriptions with the function code, time, and cost, the following points emerged:

- Elimination of facilitating honing operations by improving boring finish.
- Why rough and final hone?
- Why not bore to finish dimensions—on the powder chamber and rough forging?
- Design tube prior to autofrettage such that interior dimension after autofrettage equals final dimension.
- Tapers—why two separate operations? Why not completely finish turn OD in one operation on one machine?
- Why counterbore before autofrettage on the muzzle end?
- Why so many spots? Can they be combined using different machines, more carriages, or a different boring method?
- Why grind the powder chamber twice?
- Turning OD after swage—tape lathes; why not two carriages on one lathe?
- Would there be any advantage to modeling the manufacturing process?
- Can the milling operations on slots be combined?
- Benching of breech threads is allocated over 2 hours of time. Can this be eliminated?
- Benching of evacuator is allocated over 3 hours. Can this be eliminated?
- Taper hole, 90 degree slot or keyway on breech OD. Why both?
- There are two cleaning operations listed on the bore. Is it necessary to double clean the bore?

Potential Areas of Improvement Chosen

The review of these points led to the adoption of new projects based on the potential for considerably reducing the cost of manufacture of gun tubes.

Thus, personnel at the Arsenal are examining the elimination of honing on fine grinding operations; they are looking into the potential for elimination of excessive breech end detailing on tubes, which is used only to permit the autofrettage process to be performed; they are examining benching operations (essentially hand repairs), which were pointed out as high labor cost operations; and they are looking into dedicated material handling because the high move costs using present methods became glaringly apparent from the analysis.

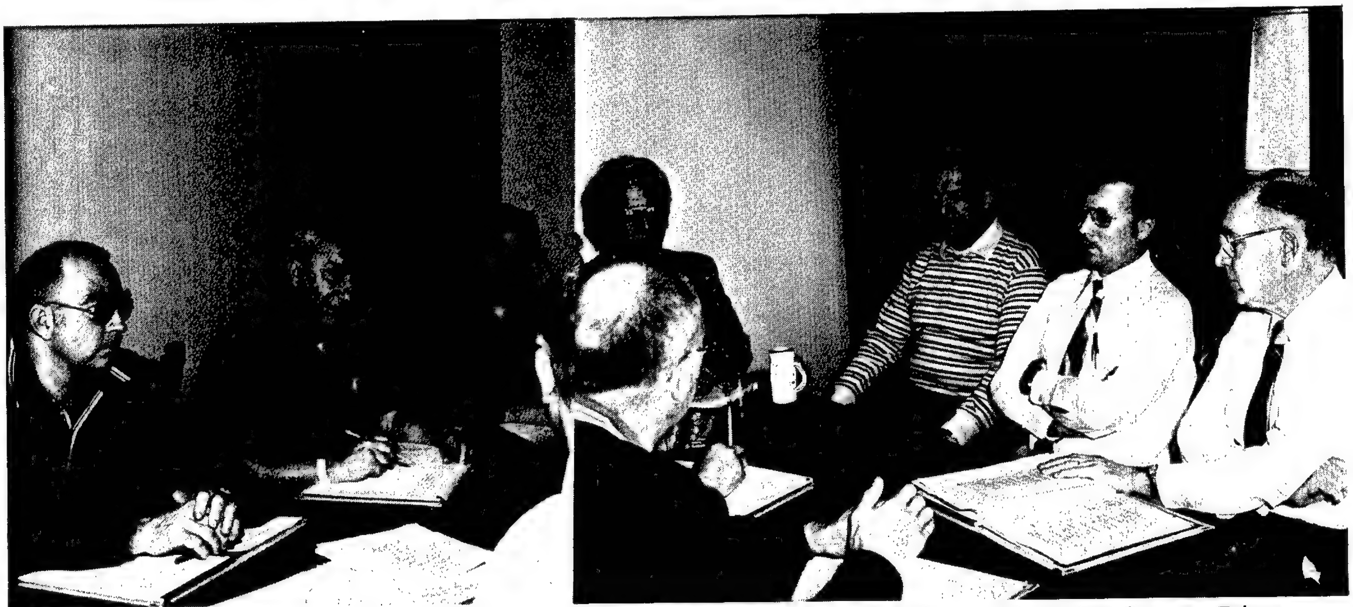
Again, it is not the purpose of this guide to solve any problems, but to help determine those areas which have the greatest potential for return on investment in improved technology.

Bibliography

Abou-Zeid, M. R., "Group Technology", **Industrial Engineering,** May 1975.

Ham, Inyong, "Comparative Evaluation of Classification and Coding Systems for Group Technology Applications", The Pennsylvania State University, November 1975.

RRC International, "Development of an End Item Manufacturing Process Guide", Contract #DAAA22-74-C-0003, Watervliet Arsenal, 1974.

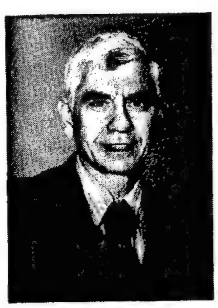


PANEL CHAIRMEN hold behind the scene working session at the Army Aviation ManTech II Conference February 18-22 in Corpus Christi. Pictured (left to right) are: Propulsion Panel Chairman Don Weidhuner of AVCO Lycoming; Conference Master of Ceremonies Richard L. Long, Deputy Director of Systems Engineering and Development at AVRADCOM; Rotor Panel Chairman Kenneth Grina of Boeing-Vertol; Conference Coordinator Robert G. Vollmer, Chief of AVRADCOM's Production Technology Programs; Airframe Panel Chairman Robert J. Torok of Sikorsky Aircraft; Aircraft Subsystem Panel Chairman Richard E. Kangas of Hughes Helicopters; and Drive Systems Panel Chairman Richard E. May of Bell Helicopter Textron.

New Horizons for MM&T

Aviation ManTech II Report

Future manufacturing trends and new directions of technology came to the fore at the U. S. Army Aviation ManTech II Conference held the week of February 18 in Corpus Christi. One of the most significant developments to come out of this meeting between representatives from industry and Government was the future technology thrust toward superplastic forming of aluminum, in sharp contrast with the traditional use of this technology to form titanium components. Cost drivers impacted heavily in establishing this new direction for manufacturing technology in the airframe sector, which included proposals for projects to develop low cost tooling. Two hundred fifteen projects ultimately were submitted by attendees—the Airframe Panel topping out with sixty-six, followed by the Propulsion Panel with fifty-four, Aircraft



GERALD A. GORLINE is a graduate Industrial Engineer with BSIE (1959) and MSIE (1966) degrees from Washington University, St. Louis. He has been responsible for managing the AVSCOM and AVRADCOM Manufacturing Technology Program during the past fourteen years. In addition, he has served as project engineer for the development of advanced manufacturing technology projects for CAD/CAM and engine and aircraft components used in Army helicopters. He has twenty-two years of manufacturing engineering experience, of which nineteen are in the aerospace industry involving both fixed wing and rotary wing manufacturing areas with aerospace firms and with the U. S. Army. He is active with the Aerospace Division, American Institute of Industrial Engineers, and the American Helicopter Society. He also is a member of the Metals Committee of the Tri-Service Manufacturing Technology Advisory Group (MTAG).

Subsystems with thirty-eight, Drive Systems with thirty-three, and the Rotor Panel with twenty-four.

Attendees From Entire Nation

Sponsored by the U. S. Army Materiel Development and Readiness Command and conducted by the Aviation Research and Development Command under the direction of MG Story C. Stevens, the conference was national in scope. Its attendees, from engine, airframe, and instrument manufacturers all over the United States, discussed new manufacturing approaches for production of Army aircraft with the Government officials.

Through its Manufacturing Methods and Technology (MM&T) programs, AVRADCOM is seeking improved manufacturing methods, processes, and equipment for production of its Army aircraft; these programs are aimed at cost reduction and improved reliability and maintainability. MM&T projects have a clear application to current or future aircraft production, ensuring that successful efforts will lower acquisition and life cycle costs.

New Contractor Incentives Provided

AVRADCOM relies largely on private contractors to develop this new manufacturing technology. Before the establishment of the MM&T program, new manufacturing technology was developed primarily through contractor funded programs. Now, however, AVRADCOM sponsors programs designed to develop and apply specific new manufacturing techniques. This approach provides greater incentive to the contractor, and it ensures transfer of the technology to the Command, which then can direct further refinement, development, and wide application of the new technology.

Designed to help AVRADCOM develop an updated five year manufacturing investment plan and to define future MM&T efforts, ManTech II is a follow-up to the previous successful ManTech I Conference held in Palo Alto in November, 1977. Participants in both working conferences included both civilian and military personnel knowledgeable in aviation manufacturing problems. The primary objectives were to identify major cost drivers and problem areas, obtain proposals, and define priorities based on the Army's requirements and potential payback. Each conference was another step toward the ultimate goal of reducing Army aviation systems costs. The significant output of each conference was a list of recommended potential projects for AVRADCOM's use in planning future investments in manufacturing technology.

Working Panel Format Used

The carefully structured working conference format provides an excellent forum for exchange of ideas. Separate panels work in five aviation technology areas (airframe, drive system, propulsion, rotor, and aircraft subsystems). Each panel is chaired by someone from a pertinent sector of the aviation industry.

AIRFRAME PANEL

The Airframe Panel considered proposals solicited from the prime helicopter manufacturers and their supporting contractors. These airframe proposals were broken down into metallic structures, nonmetallic structures, paints and finishes, data and productivity, and projects categorized as R&D Programs; the sixty-six projects reviewed were received from nineteen sources. The basic task of the panel was to review the list of potential airframe projects and rank them in order of priority.

Fixed Wing Representatives Attend

Panel Chairman was Robert J. Torok, Senior Vice President, Production Programs, Sikorsky Aircraft; members of the panel were selected from the prime Army aviation suppliers and their supporting contractors. For the first time, representatives of fixed wing manufacturers were invited to provide an expanded perspective and added balance to the panel. Also represented were members of other interested Government agencies. A planning meeting was held a few months prior to the conference to establish a rating system for project proposals. It was decided to rate four areas for each project:

- The level of dollar savings expected
- The appropriateness of the project to ManTech
- The probability of use
- The probability of success.

Each of the four areas was to be rated (1) low, (2) average, and (3) high. The product of these four scores would then be the project score. Copies of all proposed projects were forwarded to panel members for review prior to the conference.

Careful Scheduling Adhered To

Each project initiator was allowed ten minutes to present his program to the airframe panel at the conference. The thirteen panel members' scores (the Chairman abstaining) then were totaled and the proposals ranked in order of total scores. Final ranking by each panel will be

reported subsequently in a forthcoming Preliminary Report or in the Final Report for the Army Aviation ManTech II Conference.

A summary of the proposals and recommendations made by the panel for each Manufacturing Category follow below:

I. Metallic Structures. Ten proposals were submitted. The panel rated superplastic forming of aluminum and the use of low cost tooling to accomplish this process as top proposals for the Army; another strong proposal for consideration was aluminum HIP casting.

II. Nonmetallic Structures. Thirty-five proposals were submitted. Those recommended by the panel for the Army to consider for funding are listed in ranking order:

(1) Thermoplastic forming, which would encourage reduction of detailed parts and assembly operations.

(2) Improved trimming and joining operations by application of water jet cutting and hard coated drills applied to processing typical Kevlar and fiberglass composite structures (for which actual cost data exists).

(3) Improved durability and reduced costs of composite structure curing molds through application of castable reinforced ceramics and hard faced coatings on conventional epoxy fiberglass tools.

III. Data and Productivity. The program suggested in this area was development of a machining practice data base. This is needed because there is a continuing reduction in the skill level available with the metal cutting industry resulting from increased use of numerically controlled machine tools. As a consequence, the experience level of the labor base continues to erode, and a computerized compilation of successful current industry practices is needed to enhance and supplement the standard metal machining handbooks.

IV. Research and Development Program. This conference highlighted several areas which the airframe panel categorized as research and development programs. The papers presented were recognized as manufacturing concerns which are not ManTech but deserve serious Army consideration for funding. These proposals included

- Thermoplastic materials
- Chemical process techniques
- Polyimide foam
- Qualified paint (water base) systems
- Acoustic interiors.

PROPULSION PANEL

The Propulsion Panel, chaired by Don Weidhuner of AVCO Lycoming, evaluated fifty-four proposals. These first were evaluated to categorize them as MM&T, R&D, Product Improvement Program (PIP), or other. Of the fifty-four proposals, twenty-eight were considered MM&T, twenty-two R&D, and three PIP. One did not fit into any category.

MM&T proposals were evaluated further based on:

- Need for the Army
- Concept feasibility
- Probability of implementation
- Probability of success.

From this rating scheme, eight proposals were recommended for immediate funding by the Army.

Top Priority Proposals Chosen

The highest priority proposals recommended were those on the Improved Cast Turbine Wheel. Present integrally cast turbine wheel applications are Life Cycle Fatigue (LFC) limited, restricting their application to only small increases in fatigue properties and their use only where minimal costs were involved.

Great emphasis was put on technology for Dual Property Turbines. Existing technology severely limits design freedom, as in a radial turbine configuration. The opportunity to produce a ring of airfoils with direct solidification or air cooled processes integrated with LCF performance of disc materials provides significant savings in machining costs.

High importance was given to the elimination of nonmetallic inclusions in superalloys. Nonmetallic inclusions are detrimental to component reliability, emphasizing the need for cleaner alloy melting practices. These practices—presently available—could reduce manufacturing scrap and increase reliability.

Potential Areas Extensive

Centrifugal casting and hot isostatic pressing techniques also are high priority items recommended. These techniques will improve cast properties in superalloys to a point at which castings likely can replace some forgings in impellers. Cost reductions would result by eliminating the need for five axis machining.

Other areas of importance with wide industry application but not recommended for immediate Army funding are small turbine seal optimization, improvement of tur-

bine shroud materials, integral nozzle coating development, plasma surface treatment of gearing, integral wrought turbine rotor development, blisk repair, plasma spraying processes, superplastic forming diffusion bonding, corrosion resistant turbine tips for blades, ultrasonic inspection, and lamilloy process optimization for combustors.

Eight other areas were considered as presenting excellent prospects but were not recommended for funding at the present time.

AIRCRAFT SUBSYSTEMS PANEL

The Aircraft Subsystems Panel, chaired by Richard E. Kangas of Hughes Helicopters, reviewed thirty-eight proposals which involved electronic/electrical, hydraulic, and armament subsystems. Eight were regarded as not MM&T.

The panel graded the proposals primarily in four areas:

- Is/is not manufacturing technology
- Cost savings
- Probability of success
- Probability of implementation.

The grading system consisted of a one to three score, with one being low and three being high in each area. Each grade was used as a multiplier, such that the highest possible score was $3 \times 3 \times 3 \times 3 = 81$.

After scoring all proposals on this numerical basis, the top proposals again were reviewed in detail by the panel and prioritized. Also taken into account were potential energy savings, material usage, reliability, scrap reduction, and improved quality.

Plastics Underscore Breakthrough

Major emphasis was placed on reducing the high cost of machined metal parts through the use of improved plastics technology. In this area, a high performance moldable plastic would be a potential breakthrough in the manufacture of gyroscopes. Also, the use of thermoplastic molded bellcranks and other similar type items would result in tremendous savings and have wide application.

Another area of importance was in providing the use of hand held equipment versus the use of heavy bench or table mounted equipment. Both labor reduction and industry wide use are expected.

The use of computerized/semiautomated techniques on several components was another area which offered advantages in labor savings and quality control procedures. Again, in all applicable MM&T proposals priorities were placed in cost savings, probability of success, and implementation.

DRIVE SYSTEMS PANEL

The Drive Systems Panel, chaired by Richard K. May of Bell Helicopter Textron, reviewed thirty-three proposals which included transmissions, gears, bearings, shafts, and seals. Twenty-four projects were acceptable as MM&T. The proposals were ranked according to four areas:

- Cost savings
- Whether or not ManTech
- Probability of success
- Probability of implementation.

The rating system in which each area was (1) low, (2) medium, and (3) high. The highest possible score would be a ranking of three in each area, multiplied together to give a score of 81 ($3 \times 3 \times 3 \times 3$). Accordingly, the lowest possible score would be 4 ($1 \times 1 \times 1 \times 1$). The proposals were also ranked according to (1) readiness for funding, (2) tri-service funding, or (3) additional R&D needed. In the case of identical rankings, intangibles such as energy savings, reliability, and critical material usage were used as tie breakers.

Modernized Equipment the Goal

Panel recommendations included more modernized gear manufacturing equipment and technology with improved quality. This applies to CAD/CAM, investment casting, forgings, powder metallurgy, and composites.

Discussions also took place concerning future areas of importance in MM&T, such as modernized equipment specifications and establishment of more common material specifications.

ROTOR SYSTEM PANEL

Rotor Panel members chosen consisted of representatives from all major helicopter contractors and various suppliers and subcontractors. This group was chaired by Kenneth Grina of Boeing-Vertol.

The panel evaluated and ranked 24 proposals according to their merit and application. Eight of the proposals reviewed were acceptable as MM&T projects. The remaining were considered as R&D effort, had no Army application, or offered little return on investment. Nevertheless, each of the twenty-four proposals was evaluated and rated.

There were seven proposals that were recommended for funding by the panel as high priority programs. Of these, Composite Treatment and/or Manufacturing led the way, comprising four of the seven programs.

Summary Conference Panel Findings and Recommendations			
Panel	**Panel Chairman**	**Projects Submitted**	**Panel Recommendations For Technology Thrusts**
Airframe	Mr. Robert J. Torok Senior Vice President Production Programs Sikorsky Aircraft	66	• Superplastic Forming *of aluminum* including low cost tooling. • Aluminum hot isostatic pressed (HIP) casting. • Low cost techniques of thermoplastics forming. • Improved trimming and joining operations.
Propulsion	Mr. Don Weidhuner Senior Vice President Programs AVCO Lycoming	54	• Improve cast turbine wheel technology. • Fabrication of dual property turbines. • Centrifugal casting. • Hot isostatic techniques. • Eliminate nonmetal inclusions in superalloys.
Aircraft Subsystems	Mr. Richard E. Kangas Manager, Manufacturing Engineering Hughes Helicopters	38	• Eliminate high cost of machined metal parts by application of plastics technology. • Fabrication of gyroscopes with high performance moldable plastics. • Use of thermoplastics molded bell cranks and similar applications. • Employment of hand held equipment instead of bench or table equipment.
Drive Systems	Mr. Richard K. May Vice President Operations Bell Helicopter Textron	33	• Development and utilization of modern gear manufacturing equipment and technology.
Rotor	Mr. Kenneth Grina Director of Engineering Boeing Vertol Company	24	• Low cost composite main rotor blades. • Radiation cure of rotor blade coatings. • Utilization of chromatography and automatic cure cycles for consistent composite components.

The Non-Metals Subcommittee of the Department of Defense Technology Advisory Group is sponsoring a Symposium on In-Process Quality Control for Non-Metallic Materials on 30 April-1 May 1980. This symposium will concentrate on the results of DoD and NASA sponsored projects in this area of technology.

The Non-Metals Subcomittee hopes through this symposium to stimulate wider use of in-process quality control procedures in the manufacture of DoD weapons systems. The symposium will be held at the Holiday Inn-Midtown, Albuquerque, New Mexico. Reservations may be phoned in to the hotel at (505)345-3511; registration fee of $5.00 will be charged.

For further information concerning the agenda, subject matter, or meeting arrangements, contact:

Michael A. Kornitzky
Vice Chairman
Non-Metals Subcommittee
Manufacturing Technology Advisory Group
(617)923-3524 or Autovon 955-3524

Composites To Lead the Way

Low Cost Composite Main Rotor Blade was considered by the panel as the foremost program, providing industrywide application and considerable cost saving. This program listed the Wet Filament Wound Technique combined with such materials as Fiberglass Epoxy, Graphite, and a Honeycomb Core. The project hope is to demonstrate that an all-composite blade can be built and will be operated at a substantial reduction in cost.

Radiation Cure of Rotor Blade Coatings was the second program considered as high priority and having potential of considerable cost savings and industrywide application. This program would provide the radiation curable coating formulation, test data, economic justification studies, and facility design criteria for the radiation cure of rotor blade coatings. This technology is applicable to both metallic and composite rotor blade systems.

Chromatography was highly rated by the panel as having industrywide application and required to establish raw material consistency. This program will provide Gel Permeation and High Pressure Liquid Chromatography; to Quantitate the Degree of "B" Staging, Formulation Accuracy and Resin System Characterization is proposed as a methodology to control incoming materials and their storage.

Automated Systems Hold Promise

Automated Cure Cycles had similar characteristics in the area of industrywide application and cost savings. The proposed program will provide an automated system that can be adaptive to present processing equipment for monitoring and controlling Composite Cure Cycles. This system has been listed in monitoring the cure of production Graphite-Epoxy Tail Rotor Spars as well as the cure of heavy section test laminates for the press grade graphite competition currently being conducted by CM&D.

The final three proposals which were rated highly by the panel were Superplastic Formings/Co-Diffusion Bonding of Titanium Sheets (SPF/CDBT), Investment Casting With HIP, and Electronic Blade Balance System.

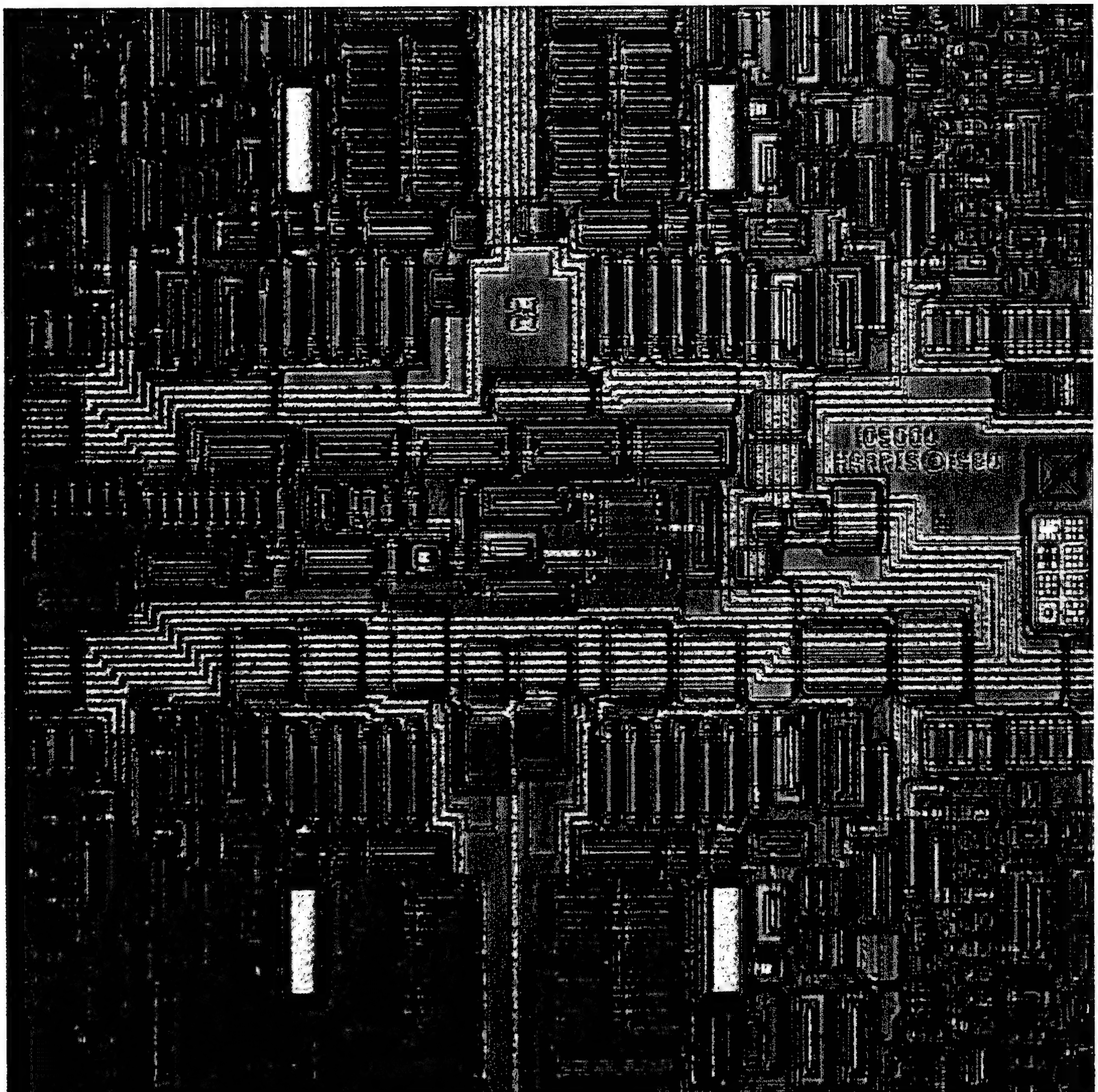
Inspiration as well as information was provided in special addresses at the conference. The Keynote Session featured a special address by Dr. Walter B. LaBerge, Principal Under Secretary of Defense for Research and Engineering. At the luncheon, Mr. Fred W. Randall, Jr., Vice President, Subcontracts, Vought Corporation, presented his views on ManTech programs. Mr. Gerhart Neuman, Vice President, Special Projects, General Electric Company, delivered the speech at the Thursday evening Banquet.

US Army

ManTech Journal

New Directions in Circuitry Materials

Volume 4/Number 3/1979



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US Army
ManTech Journal

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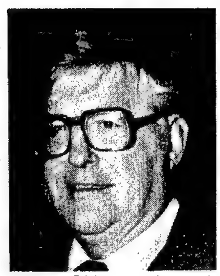
Inside Back Cover—Upcoming Events

ABOUT THE COVER:

The tiny (135 x 125 mil) LSI device shown on the cover is a Limit Sum Amplifier developed for the U. S. Army Missile Command by Martin-Marietta. It is one of six custom linear bipolar circuits which are utilized in the Army's Copperhead and Hellfire missiles and the Navy's Guided Projectiles programs. These linear circuits are fabricated using dielectrically isolated bipolar processing. The system constraints require that each of the four channels be gain matched over several orders of dynamic range with minimum noise. This device contains two amplifiers per channel.

Comments by the Editor


DR. JOHN J. BURKE

It's a delight for the staff of the Army ManTech Journal to again feature the work of the Army Missile Command in one of our issues. Exactly nine issues have been published since the second issue of this magazine, in which MICOM work was highlighted. A visit several months ago by our editorial staff to the Missile Command at Redstone Arsenal produced a remarkable number of projects to be reported in the ManTech Journal. The people at MICOM have been busily engaged during these past three years turning out technology that will produce significant savings from MM&T implementation.

Some of the new directions discussed in the lead articles by Charles Riley, Colonel Benjamin Pellegrini, and Dr. Victor Ruwe reflect programs and planning for the future that will bring large savings in the Army's manufacture of electronics components. Widespread use of microelectronics in our new sophisticated weapons, introduction of less expensive substitutes for gold contacts, and producibility design in circuitry will have a profound effect on the costs associated with electronics production in coming years. MICOM is to be commended on the outstanding results they are producing with their well managed manufacturing technology programs.

Weight and cost savings in phased array antennas produced using new technology described in the article on microwave circuits by Richard Kotler and increased reliability thru more effective testing using infrared imaging as described in the article by Gordon Little are two more benefits arising directly from MICOM MM&T programs. And the article by Bill Crownover on filament winding of rocket motorcases beautifully illustrates how a clearly defined objective can be attained thru a military sponsored manufacturing technology program—in this case, the establishment of a capability to mass produce these small but highly loaded components.

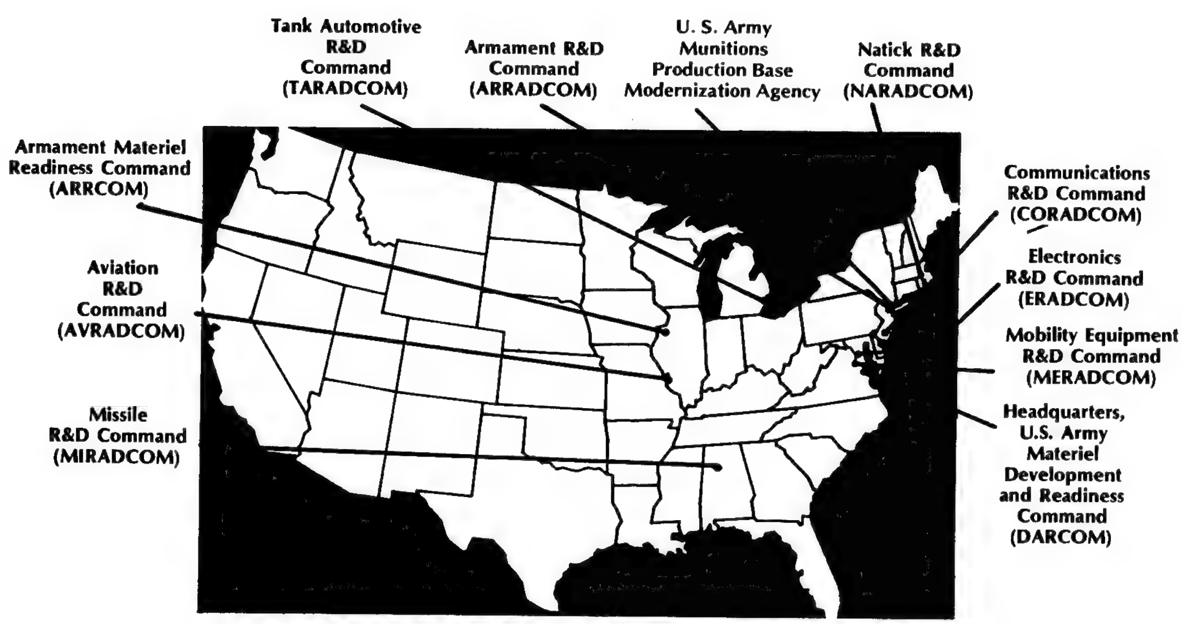
A brief note of acknowledgment on one of the best known early mantech proponents from the DARCOM MTO is a special feature of this issue, and it represents a first. Ed Gardner has a long record of being a forerunner in everything he ever undertook, and the noting of his retirement in the ManTech Journal also is consistent with his style.

The index of subjects carried in this issue of the magazine responds to the requests of numerous libraries that receive the Army ManTech Journal. We think such an index should prove helpful to those who wish to check out specific topics on manufacturing

technology in the Army commands. The index covers every topic referred to in the first eleven issues, and it will be updated periodically in the future as more and more articles are carried on related subjects.

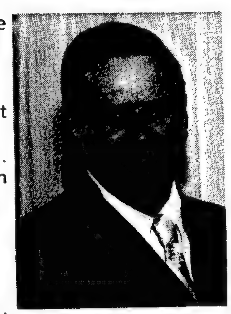
The next forthcoming issue of the Army ManTech Journal will feature several more articles from the Missile Command and the Electronics Research and Development Command, along with several articles on metalworking, which were taken from papers presented at the Tri-Service Conference on Metalworking held last September. A special article on the metal nitride oxide semiconductor block oriented random access module (MNOS BORAM) developed at ERADCOM will furnish some interesting reading for subscribers, and the metalworking articles will cover powder metallurgy, wrought metal, and molten metal developments. We are looking forward to the publication of an unusual offering of articles in that issue—our fourth and last one for the year.

DARCOM Commands Actively Implementing New Manufacturing Technology Methods



New Systems Are Smarter

Microelectronics Critical to New Weaponry



CHARLES E. RILEY has been Director of the Engineering Directorate at the U. S. Army Missile Command since its inception in late 1979. Prior to this assignment, he served as Director of the Advanced Systems Development and Manufacturing Technology Directorate at MICOM and the Engineering Laboratory. He earlier had been an aeronautical research engineer and supervisor in the Guidance and Control Directorate of the Engineering Lab. After receiving his B.S. in Mechanical Engineering in 1955 from Auburn University, he joined Wolverine Tube Division in Decatur before coming to work at the Missile Command. He received his M.S. in Engineering Management from Vanderbilt University in 1970. During his 25 year career at MICOM, he has initiated a directorate computer management system utilizing highly specialized and complex software algorithms, a tri-service program for elimination of precious metal (gold) from electronic devices, and a tri-service CAD/CAM umbrella program to resolve critical electronic design fabrication problems. He also has conducted significant research and development on optics fabrication and testing at MICOM and has published work on noise in optical insulators. Mr. Riley has worked on developing the optimal transition of missile systems from R&D into production and has developed and is executing a plan to resolve problems in availability of custom hybrid electronic chips. He also has published work on the characterization and modeling of low frequency noise in thick film resistors, thermal resistivity of hybrids, and guidance and control technology planning. He holds a 1964 patent on a multi-internal switch activator and has been named Eminent Engineer by Tau Beta Pi. He is a member of the Federal Laboratory Consortium for Technology Transfer and serves as Advisor to the Electrical Engineering and Mechanical Engineering departments at Auburn University.

Military weapons are in the midst of a metamorphosis. Significant changes are occurring which have far reaching implications. Although advances are being made on many fronts, none has so drastic an impact as that produced by the widespread integration of microelectronics into the weapon arsenal. Microelectronics provides the brainpower for new high performance weapons. These smart weapons are not only becoming more intelligent, but because of the use of microcircuit technology, they can be packaged in a smaller volume.

LSI A Necessity, Not A Luxury

Current and future mission requirements—coupled with budget constraints—dictate that military weapon systems must be low cost, small size, lightweight, extremely reliable high performance units. These requirements drive the design toward increased use of microelectronics, where significant increases in circuit density, reliability, and performance are accompanied by steady decreases in both cost and size.

A significant portion of the cost of a missile system, for example, is in the electronics control, guidance, and instrumentation systems. Microelectronics therefore plays a very fundamental role in the arena of military weapons, and there can be no doubt that future weapon systems will be even more critically dependent upon this high technology.

The extensive use of large scale integration (LSI) in future weapon systems is therefore not a luxury, but a necessity. It is essentially a constraint in that it is a necessary condition for weapon system superiority.

Multiple Courses of Action Pursued

In order to insure that microelectronics will remain viable in this environment, problems which are attendant to this technology must be solved in a cost effective and timely manner. Typical courses of action currently being pursued are the DOD program in very high speed integrated circuits (VHSIC), the extensive use of computer aided design/computer aided manufacturing (CAD/CAM), and elimination of the use of precious metals.

If the modern weapon system development programs are to produce cost effective weapons which possess the proper performance indices, then microelectronics must be continuously enhanced, because weapon system development is critically coupled to the advancement of this technology.

Alternate Strategies Recommended

Precious Metals to Be Eliminated?

COLONEL (P) BENJAMIN J. PELLEGRINI currently is Deputy Commanding General for Research and Development, U. S. Army Missile Command. He was commissioned in Air Defense Artillery after receiving his B.S. Degree from the U. S. Military Academy in 1958. He received M.S. and Ph.D. degrees in Nuclear Physics from Tulane University in 1965 and 1970, attended the Armed Forces Staff College in 1973, and the National War College in 1977. A member of Sigma Pi Sigma, he has special expertise in atomic energy research and development and advanced simulation concepts/plasma physics. Previous assignments include Project Manager, HELLFIRE/Ground Laser Designator Project Office (1977-79), Military Assistant to the Secretary of the Army (1975-76), High Energy Laser DASC, Office of the Deputy Chief of Staff for Research, Development and Acquisition (1974-75), Commanding Officer, 2nd Battalion (C/V) (SP), 61st Artillery, 2nd Infantry Division, Korea (1973-74), and Physicist, HQ, Defense Nuclear Agency, Casino Program/Advanced Nuclear Simulation Concepts (1970-73).

Precious metals is a term that generally is used to describe the platinum group of noble metals including gold, silver, platinum, palladium, ruthenium, iridium, and osmium. These metals generally exist in a free state and resist the action of acids and alkalies. The prices of these metals (especially gold and silver) recently have fluctuated wildly, and their costs in general are at least twice what they were a few years ago. In addition to these skyrocketing costs, consumer demand has severely reduced many precious metal reserves, and these conditions are further complicated by the fact that the metals are found in third world nations characterized by unstable governments.

The importance of these circumstances stems from the fact these precious metals are used extensively in military grade hybrid microcircuits, which in turn are a myriad of ways in the Army's modern weapon arsenal.

Precious Metal Supplies Questionable

The principal applications of precious metals for government thick film hybrid microcircuits are listed in Table 1. It is obvious from an examination of this table that precious metals play a very central role in the construction of hybrid microcircuits for government use. However, the availability of these metals is somewhat tenuous. Because of its relationship to international monetary standards, the gold supply problem is fairly well known. Platinum is difficult to obtain and at times must be purchased on the "grey market." Ruthenium comes from South Africa and palladium is mined in both the Soviet Union and South Africa. The supply lines from either of these two countries could easily become extremely fragile.

TABLE 1	
Precious Metals	
Precious Metal	**Principal Applications**
Gold	Thick film conductors Bonding wire Plating for metal packages Bonding alloys in the form of gold/tin Components
Platinum/Gold	Thick film conductors Components
Silver	Thick film conductors Components
Palladium/Gold	Thick film conductors Components
Palladium/Silver	Thick film conductors Components
Ruthenium mixed with bismuth oxide and other trace elements	Thick film resistors Components
Iridium mixed with bismuth oxide and other trace elements	Thick film resistors Components
Osmium	Probe Tips Low conductivity connector contacts Components

Table 1

Properties Ideal For Hybrids

There are numerous reasons why precious metals are universally employed in military hybrid microcircuits. In general, their presence yields special features which are of critical importance in the construction and performance of the electronics.

Table 2 provides a list of pertinent technical characteristics for some of the more important precious metals and the most promising candidate substitutes. As a general rule it is desirable to have the cost low, the coverage high, the resistivity low, thermosonic and ultrasonic bonding high, and adhesion high.

There are other technical features which are very important in the construction of hybrids. Consider for example the characteristics which enhance the usefulness of gold. Gold is an inert material, it will not react with the environment over typical processing temperatures, and its conductivity is exceptional. Gold prints well, either in multilayer hybrids or fineline. The termination effect from gold to resistor material is good, and its bonding characteristics with aluminum are excellent. The other materials on the left side of Table 2 also have similar positive features that make them viable. However, an examination of the cost index in this table clearly indicates that there is potential for enormous savings in the construction of military hybrids if these precious metals can somehow be replaced with the materials on the right side of the table.

Substitute Materials Marked By Compromise

The materials which are candidate substitutes for the critical metals exhibit potential, but in general their use requires the solution of a number of attendant problems.

Silver has good printing characteristics, is bondable, and has good adhesion. It can be used to improve the solderability—in the solder pad areas only—on nickel and alumi-

	Precious Metals						Candidate Substitutes				
Parameter	Gold	Platinum/ Gold	Palladium/ Gold	Palladium/ Silver	Platinum/ Silver	Silver	Nickel	Copper	Aluminum	Dielectric	Remarks
Cost, dollars/g	19.50	19.89	18.21	2.25	1.25	0.50	0.50	0.50	0.50	0.75	
Coverage, g/cm^2	50	70	50	70	70	60	45	45	40	80	
Average Resistivity, $m\Omega/cm^2$	3.0	25	25	50	10	3	50*	24*	40*		*Nitrogen fired
Thermosonic bonding (1 mil gold wire bonded)	12	12	12	9	7-19	8	5*	—	8*	—	Pull test measured in grams *Overprinted with silver on bonding pad
Ultrasonic bonding (Aluminum wire with 1 percent silicon)	12-14	12	12	6-7 Not recommended	10	11	6*	—	7*	—	Pull test measured in grams *Overprinted with silver on bonding pad
Solder teaching	Poor	Good	Fair	Good	Fair	Fair	?	?	?	—	
Adhesion in lb	—	3.5	3.5	4–6	4-6	5-7	?	?	?	—	On a 100 x 100 mil pad using a 100 mil wide strap
— Not applicable ? Unknown at present											

Table 2

num if it is cofired. However, migration is a problem, especially on a multilayer thick film hybrid, and no dielectric currently being used will work with this metal on a multilayer design.

Copper, nickel, and aluminum all can be airfired but will not solder, and high resistivity is a real problem. In forming gas, copper will solder very well, but it solders only marginally in a nitrogen atmosphere. Copper fires on ceramic at 850 to 1000 C and on soda lime glass at 500 C. Soda lime glass cannot withstand temperatures which exceed 500 C. Nickel fires on ceramic at 925 C. Aluminum is low firing at 580 to 610 C on ceramic. The importance of the firing temperature stems from the fact that it affects solderability, bondability, and adhesion.

At the present time there is no good dielectric or resistor system which has been developed for use with copper, nickel, or aluminum. Good resistor systems typically fire at 850 C.

Dramatic Cost Savings Possible

Table 3 illustrates the relative cost of a "typical hybrid" using different materials. The costs for labor, equipment, substrate, and glass are common, therefore the comparison is based upon metallization per layer. Metallization is in turn based upon coverage, since every metal covers a different amount of area. The last column in the table clearly illustrates the need for the employment of new materials in view of the enormous number of hybrids currently employed and the staggering increases in thick film hybrid microcircuits necessary for the future as the weapon systems become more sophisticated and intelligent. For example, under the assumption that gold reaches $800 per ounce by 1984 and that no technological changes are initiated to offset the need for this metal, it is projected that during that year the government will procure 158 million dollars worth of gold for hybrid microelectronics. This figure compares with 77 million

Metal	Material Used, grams	Scrap, grams	Total Material used, grams	Cost/g, Dollars	Cost per Layer of Substitute, Dollars
Gold	0.30	0.09	0.39	$19.50	$7.61
Palladium/Gold	0.21	0.04	0.25	$18.21	$4.55
Platinum/Gold	0.25	0.05	0.30	$16.89	$5.10
Palladium/Silver	0.21	0.04	0.25	$ 2.25	$0.55
Platinum/Silver	0.21	0.04	0.25	$ 1.25	$0.31
Silver	0.25	0.05	0.30	$ 0.50	$0.15
Copper, Aluminum, Dielectric, or Nickel	0.29	0.08	0.37	$ 0.50	$0.19

Table 3

dollars in 1977—an increase of more than an order of magnitude in only seven years.

Although their potential for cost savings is great, there are many serious technical deficiencies and problems associated with the use of these metals. In order to make them viable substitutes, a well designed program should be established and funded to alleviate the drawbacks inherent in their use.

Processing, Reliability Effects Paramount

The development of alternate strategies for the elimination/substitution of precious metals involves not only the materials but the processing parameters and procedures, since any change in materials would drastically affect the processing techniques and reliability, which would have to be completely reevaluated. Therefore, any proposed solution to the general problem must of necessity consider all aspects of these two separate, distinct areas.

In the materials area, consideration must be given to replacement strategies for the following: **bonding wire**—the replacement of gold with aluminum or new alloys; **die attach**—the elimination of gold and silver filled epoxies and their replacement with copper, aluminum, tin, or other fillers; **package materials**—the replacement of kovar with stainless steel or other steels, the development of glass seal materials compatible with the package material, and the creative use of ceramics; **package plating**—the elimination of the use of gold through investigations of alternate plating materials, and the exploration of the use of alternate corrosion protection materials by conformal coatings such as acrylics, polyurethane, epoxy, and silicone resins.

Thorough Evaluations The Key

Considerations for processing, assembly, and packaging techniques for use with substitute materials include the following: **screen printing**—the development of a new

system capable of fineline printing with minimum bleedout and the examination of changes in such items as screen mesh, emulsions, and types of squeegees; **firing**—the determination and control of the proper atmosphere, slope of heating and cooling rates, and time at temperature; **trimming**—the development of laser or sand trimming techniques and the development and production of resistors with the proper temperature characteristics of resistance (TCR), drift, noise factor, and voltage coefficient of resistance (VCR); **component attachment**—the development of attachment techniques for use with new materials; **wirebonding**—the development of new bonding tools and the establishment of the proper wire handling techniques; and **sealing**—the development of application techniques, subject to the proper environment requirements.

The materials and processes must be optimized not only to produce cost effective microcircuits, but hybrids that have excellent reliability and are capable of surviving in hazardous environments—for example, those employed in a guided projectile. Reliability is critically important and is a significant cost driver. Gold is very reliable. However, if the gold is replaced with other materials, then these other materials must be carefully evaluated to make sure that their reliability is sufficient for the environment in which they will be used.

Specific Projects Outlined

A number of projects could be initiated immediately to alleviate precious metal problems and to establish the basis for long term alternate solutions. These projects would normally evolve from research and development to manufacturing methods and technology programs.

- Critical analysis of precious metals used in government hybrid microcircuits, including a cost analysis projection for continued use and an economic analysis which projects the impact of alternate materials and/or processes.
- Research and development of new thick film ink systems as alternatives to precious metal systems. This would include an evaluation of the possibility of screen printing thick film conductors thinner—perhaps fifty percent of present thicknesses—and carefully documenting all key parameters such as adhesion, conductivity, bondability, and solderability.
- Development of aluminum fine wire which can be used to bond chip components in a military thick film hybrid microcircuit and determination of the reliability of its bonding characteristics.
- Development of alternative package and plating materials which offer hermeticity and sealability commensurate with government standards and applications; evaluation of the use of ceramic and steel packages in place of kovar packages and the use of nickel plating as an alternative to gold plating.
- Review of multilayer thick film design techniques to evaluate the use of an overglaze to prevent the oxidation of nonprecious thick film metal conductors.
- Evaluation of the solder assembly of hermetically sealed packaged components to thick film multilayer substrates.

Opportunity For Future Savings Enormous

The various aspects surrounding the elimination of precious metals from government hybrid microcircuits have been discussed. Alternate strategies have been presented, and recommendations—which can be implemented through R&D and MM&T programs—for alleviating the problems inherent in such a transition have been outlined. The timely elimination of these precious metals and their replacement with cost effective materials provides the government with a significant opportunity for enormous savings in the future development of weapon systems.

DR. VICTOR W. RUWE has held a number of responsible positions with the U. S. Army Missile Command since 1966, where he currently is responsible for the management of research, development, engineering, and design in microelectronic development. Dr. Ruwe is a senior member of the Institute of Electrical and Electronic Engineers and the American Institute of Industrial Engineers, an officer in the International Society for Hybrid Microelectronics, a registered professional engineer, the author of numerous journal papers, international and national conference presentations, and technical reports, and has served on important DoD panels. He also holds several patents, letters of appreciation, outstanding performance appraisals, and scientific and engineering achievement awards. Dr. Ruwe has been elected to the Advisory Committee and is an Associate Editor of the IEEE Component Hybrid and Manufacturing Technology Group. In 1979, he was an individual recipient of the Army Science and Engineering Achievement award. He also has been selected and is participating in the Army executive development program. Dr. Ruwe joined Chrysler Corporation, Huntsville, Alabama, as a Design Engineer in 1962 and was promoted to Lead Engineer in 1963. In 1964, he became a Project Manager with General Electric Company, Huntsville, Alabama. He received the B.E.E. Degree from Auburn University, Auburn, Alabama, in 1961, and two M.S.E. Degrees from the University of Alabama at Huntsville, Alabama, with majors in Electrical Engineering and Engineering Management in 1968 and 1974, respectively. He completed his Ph.D. Degree at the University of Alabama in Huntsville with a major in Systems Engineering in 1979.

Producibility Included in Design

LSI Circuits for Custom Use

The process of transferring advanced custom large scale integrated (LSI) circuits from the design development phase into the manufacturing environment poses major challenges. Custom LSI circuits are by definition unique in circuit design fabrication processing or application and are used in situations where industry standard LSI circuits will not meet the requirements. Often these circuits are used in electronic systems which are being produced to a stringent schedule, thus requiring them to be designed under time constraints. This can result in a design developed with less than optimum computer simulation, process modeling, and worst case analysis. The resulting custom LSI circuits may therefore have design and/or performance deficiencies, be difficult to produce at reasonable yield, and/or may be poorly documented with testability problems.

The LSI amplifier and limit sum circuits used in guided projectiles serve to illustrate some of the problems associated with the development of custom LSI circuits. At the end of the Copperhead engineering development phase the high performance linear, dielectrically isolated bipolar circuits were found to be very difficult to produce at reasonable yield. A manufacturing technology program was initiated to address these problems, including topology and process modifications, yield and producibility improvement, test method improvements, and documentation.

Computer Simulation Mandatory

Often, LSI circuits are not designed with attention to producibility; manufacturability must be designed into a custom LSI circuit from the outset. The circuit should be completely analyzed by computer simulation to determine the optimum circuit component values, and the sensitivity of circuit performance to component and temperature variations. As a result of this analysis, topology and process modifications may be required to optimize the circuit components and improve circuit performance. Sometimes, slight variations in the topological layout of a custom LSI circuit or modifications to the standard fabrication process produce a significant impact on yield, testing, and ease of manufacture.

After the topology and process modifications have been completed, assessment of the impact of these changes on the circuit yield and performance must be determined. A series of wafer lots should be fabricated which are separated by sufficient time in order to experience the whole range of processing variables. This provides important data on the effects of process variations such as junction depth, sheet resistivities, alignment tolerances, starting material, etc., on the circuit performance and yield. From this data the sensitive process parameters can be determined and optimized.

Test Procedures and Documentation Unique

High performance custom LSI circuits often pose unique testing problems. Anticipating these problems and insuring testability in the design can ease the transition of the circuit into manufacture. In the design phase the test methods are usually manually oriented and very operator dependent. In the transition to production, new test methods must be developed and correlated to the previous bench methods. Often, the wafer probe tests must be improved in order to minimize the number of bad dies which proceed into assembly. Production test equipment requires special care with use on high performance circuits to ensure that oscillations and measurement errors are minimized.

Proper documentation of LSI custom circuits is essential, yet it often is neglected. Because a custom circuit is unique, there is often no other similar circuit and proper documentation is all the more essential. This includes well defined descriptions of the fabrication process, the lot process transfer, the wafer probe test, the final electrical test, the visual inspections, acceptance criteria, and the packaging sequence.

Proprietary Factor Means Negotiation

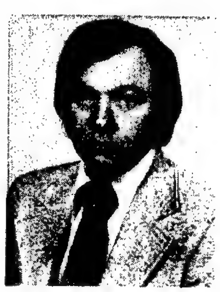
Much of the data required for complete characterization of a custom LSI circuit is considered by the various semiconductor manufacturers to be confidential or proprietary. This requires careful negotiations between the semiconductor supplier and the customer to develop an understanding of what information is and is not included as customer property in custom LSI development. The problem is further complicated by the fact that high technology processes are often unique to a particular semiconductor manufacturer, thus a design developed for fabrication at one supplier cannot be transferred easily to another.

Many of the generic producibility problems associated with the LSI preamplifier and limit sum circuits have been resolved by a manufacturing technology program funded by the Missile Command. This program addressed the items mentioned and has impacted circuit production yield as well as circuit reliability; it exemplifies how manufacturing technology contracts can improve the producibility of custom LSI microcircuits as well as ease their transition from the developmental to the manufacturing environment. The success of this MT program illustrates how, with cooperation and careful planning, potential problems between the customer and LSI supplier can be avoided and the producibility and performance of the LSI circuits improved.

Lightweight Phased Arrays Practical

Microwave Circuits on Ceramic Substrates

RICHARD A. KOTLER is Manager, Manufacturing Technology, Engineering Directorate of the U. S. Army Missile Command. After joining MICOM following his graduation in 1967 from Tennessee Technological University in Industrial Engineering, he has held continually more responsible positions in numerical control and computer aided manufacturing programs, printed circuits, and hybrid microcircuits; he is a member of the International Society for Hybrid Microcircuits. He received his MBA from Vanderbilt this past year, and serves as Coordinator of Command MICOM Manufacturing Methods and Technology programs.



Critical weight savings in the Army's AN-TPQ37 Firefinder radar and the Navy's AEGIS missile system amount to 40 and 50 percent, respectively, following completion of a manufacturing technology program funded by the U. S. Army Missile Command (MICOM). Savings of $10,000,000 also will result as high rate production gets under way. A 61% reduction in cost has been projected. The MT program has enabled MICOM to select materials, processes, and techniques for optimum production of low loss microwave microstrip circuits on ceramic substrates.

The feasibility of producing these low cost, lightweight phased array antennas has been demonstrated by Hughes Aircraft Company. The device is used to detect artillery, but the technology has general application to microwave circuits in filters, combining networks, and amplifiers. However, the primary application has been for the production of an integrated phase shifter radiating element for phased array antenna modules.

The technology developed by Hughes lends itself extremely well to manufacturing techniques because it encompasses all of the various facets, tolerances, and intricacies of the most sophisticated microwave circuits. In addition, it has the potential of significantly reducing the cost of phased array antennas, which comprise a large fraction of the cost of modern radars such as those used in the AN-TPQ37 and AEGIS. The transfer of the new technology from Hughes' Fullerton facility to that at Newport Beach has been highly successful. A large phased array antenna composed of integrated subarray modules as basic building blocks is illustrated in Figure 1.

Better Processes The Key

During Phase I of the program, various manufacturing methods for producing the integrated phase shifter radiator elements were investigated. A subarray module consisting of 64 phase shifter radiating elements was built and tested. A low cost thick film printing process in conjunction with a prepunched ceramic substrate was selected as the baseline manufacturing approach. Phase II of the program was aimed at verifying the effectiveness of the manufacturing processes and techniques selected in Phase I by producing two additional modules on a pilot production line. As a part of Phase II, a cost analysis for producing large quantities of these modules was performed.

Phase Shifter Concept In Action

A modern phased array antenna consists of a large number of similar radiating elements which are individually controlled electronically in phase and amplitude. An electronically steered phased array antenna permits the radar system to track a great multiplicity of targets, illuminate a number of targets with RF energy, and guide missiles toward them. At the same time it may perform complete hemispherical search with automatic target selection, and it even may act as a communication system directing high gain beams toward distant receivers and transmitters.

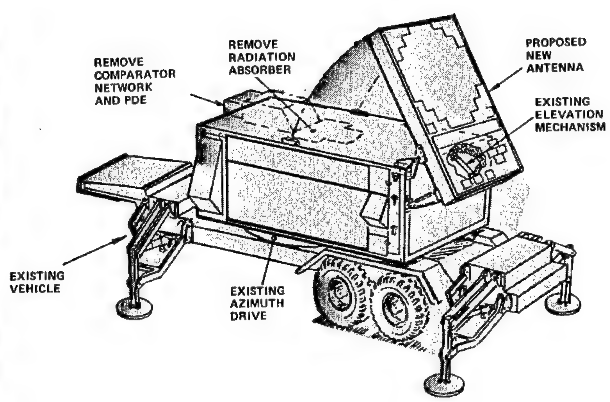


Figure 1

The basic RF component in the phased array antenna system which permits the inertialess movement of a high gain beam through space at microsecond rates is the phase shifter. The basic function of the phase shifter is to change its electrical path length upon command from the computer. A phased array system typically will have a phase shifter for every radiating element.

High Volume At Low Cost

Since typically there are thousands of identical phase shifters and radiating elements in a phased array antenna, a reduction in cost of these components would result in significant reductions in the cost of phased array antennas. Furthermore, if the fabrication technique provides for more than one phase shifter radiating element to be produced as an integrated unit, the cost would be reduced further. A Hughes phase shifter radiating element has been shown to be ideally suited for mass production using these techniques. It has been demonstrated that phase shifter radiating elements could be fabricated using low cost techniques.

The element lends itself to high volume production since it can be produced by thick film batch processing methods. Thirty two of the elements are assembled into one common housing and are fed from a compact lightweight air stripline feed. This entire assembly is handled as a basic replaceable subarray module in a large antenna. RF testing is performed on the subarray module as a unit and not on the individual components. Automatic DC continuity tests are made on each individual substrate before assemblage into the array module. Using this subarray module as a basic building block, an antenna of any size or shape can be formed by stacking them together.

The use of fast switching, reciprocal diode phase shifters also provides rapid data rate with no limitation in minimum range performance. Other merits of this approach are (1) a lightweight and compact antenna, (2) cost reduction through minimizing the number of different types of modules, thereby reducing spares requirements, and (3) improved reliability and assembly cost reduction because of the elimination of interconnecting cables and connectors.

Process Investigation Highlight

A flow diagram for the overall process and summary of the various investigations conducted during the program are shown in Figure 2. The key items in the selected process are also given in Figure 2. The major effort in the program is centered around process investigations on the integrated phase shifter radiator element. The major steps involved in the integrated phase shifter radiator elements include (1) substrate fabrication; (2) substrate metallization; (3) assembly of diodes, capacitors, and mechanical parts; (4) conformal coating; and (5) testing.

As a direct result of selecting the thick film printing process, the mounting of capacitors becomes an integral part of the substrate metallization process. The final assembly of the module consists of mounting the RF feeds, bias distribution board, and 32 dual integrated phase shifter radiator elements to the die case frame housing.

Substrate Shrunk To Size

The substrate is made from 99.5% alumina material 25 mils thick with a chamfered rectangular cross section of 1.0 by 2.2 inches. There are a total of 29 holes in the substrate ranging from 15 to 50 mils in diameter.

A flow diagram showing the process for making the substrate is shown in Figure 3. The process starts with pure alumina powder which is mixed to give 99.5 percent alumina. This then is ground and mixed with binders and plasticizers to form a slurry mixture. The mixture then is spread on a glass slide under a doctor blade and oven dried, then peeled from the glass slide. At this stage, the material is a very flexible rubber like substance. It then is punched to form all the holes and the outside dimensions.

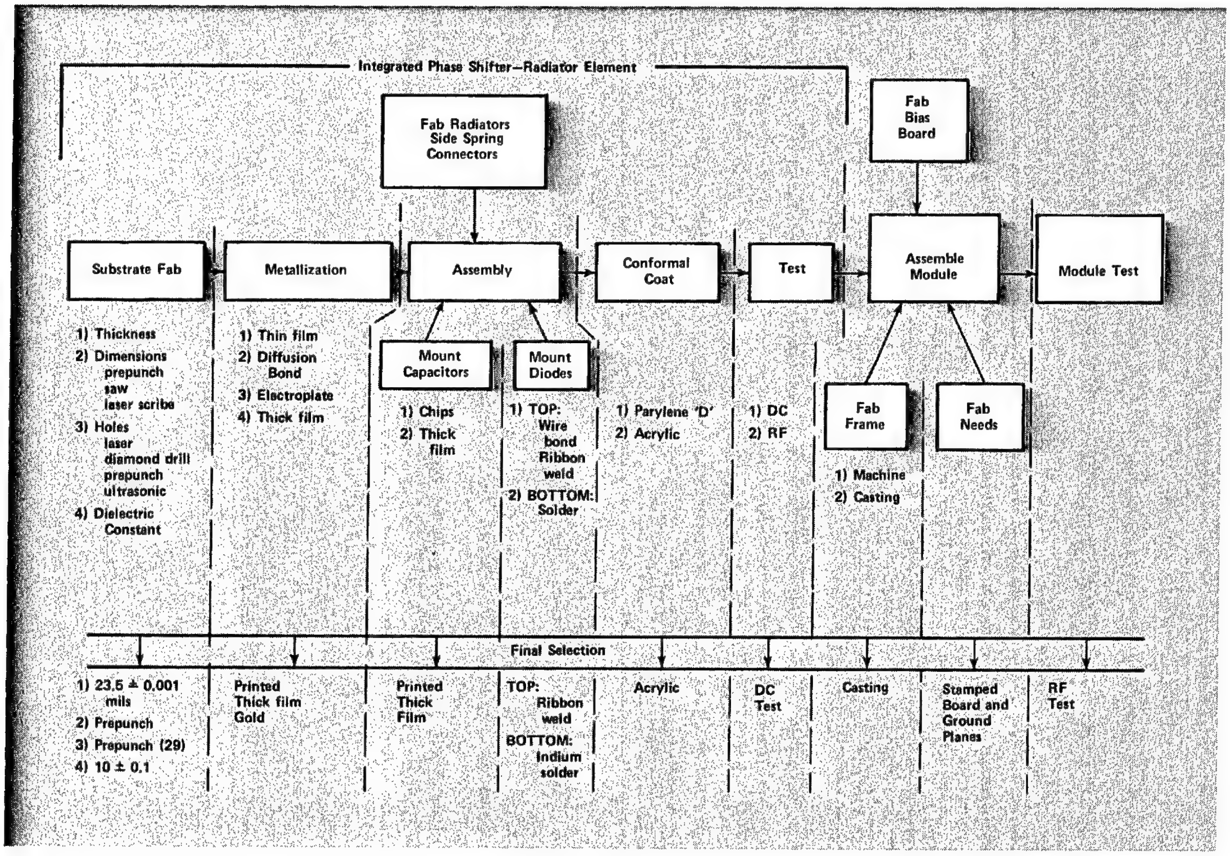


Figure 2

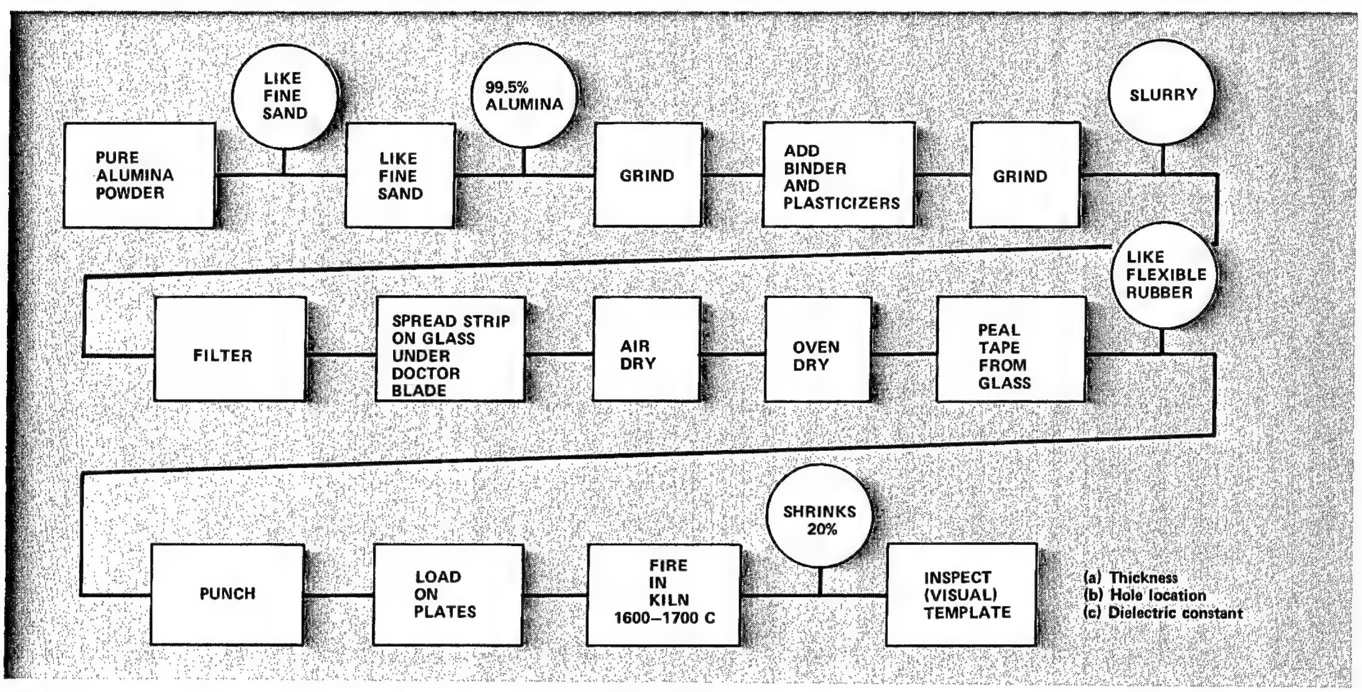


Figure 3

The substrates then are loaded on plates and fired in a kiln at 1600 to 1700 C. The substrate shrinks in all dimensions consistently by about 20 percent. Figure 4 shows the prepunched substrate before and after firing. After removal from the kiln the units are inspected for thickness, hole location, and dielectric constant.

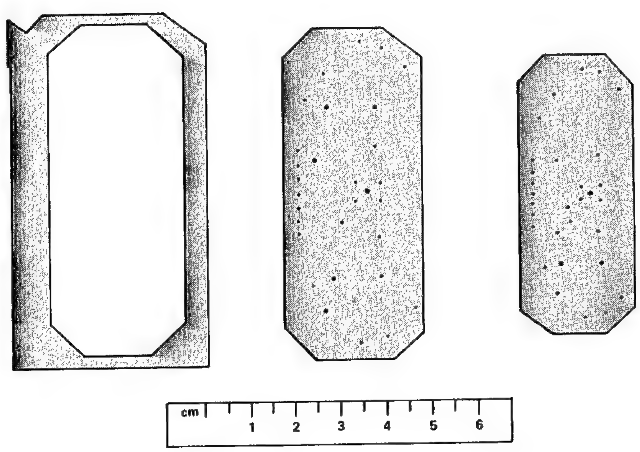


Figure 4

VARIABLE	TOLERANCE	COSTS	COMMENTS
DIMENSIONS			
PRECUT	± 1/2% NLT ± 0.003"	1.0 REF	
SAW	± 0.002" INDIVIDUAL ± 0.005" GANGED	1.5	
LASER SCRIBE	± 007"	1.2	
HOLES*			
LASER DRILL	± 0.002" DIAMETER ± 0.003" LOCATION	6	HOLE QUALITY POOR
DIAMOND DRILL	± 0.001" DIAMETER ± 0.002" LOCATION	90	SMALL HOLES DIFFICULT
SAND DRILL	± 0.003" DIAMETER ± 0.002" LOCATION	13	CYLINDRICAL HOLES IMPOSSIBLE
PRE-PUNCH	± 0.003" DIAMETER 1/2% OF DISTANCE	1.0 REF	
ULTRASONIC	± 0.003" DIAMETER ± 0.002" LOCATION	16	

* 5000 UNITS WITH 29 HOLES EACH

Figure 5

Prepunched Substrate Best

Figure 5 summarizes the results of the alumina substrate processing investigation. The prepunched process turned out to be less expensive than the saw or laser scribe operation by a factor of over 20 percent.

The dual element substrate has a total of 29 holes. The methods considered for putting these holes in the alumina substrates included laser drilling, diamond drilling, sandblast drilling, substrate prepunching, and ultrasonic drilling. The prepunched method turned out to be the least expensive, and the next closest competition in terms of cost is laser drilling. However, laser drilled holes were of poor quality and tended to induce microcracks.

As the chart in Figure 5 indicates, the prepunched substrate is the least expensive approach and is much less costly than its nearest competitor based on a quantity of 5,000 substrates with 29 holes each.

Metallization Investigated

Four different types of metallization were investigated. They included thin film, thick film, electroplate, and diffusion bond. The thin film process involved sputtering gold or copper over a thin adhesive layer. The thick film process used a screening process where the metal film in paste form is pushed through a screen that defines the circuit layout; after drying, the screened metal is fired at a high temperature. The electroplate process involved plating directly to the substrate after it had been etched or mechanically roughened. The diffusion bonding process consisted of firing a copper plated substrate at a high temperature in an oven.

Figure 6 summarizes the various metallization techniques that were tried. All the metal systems require discrete capacitors, except the thick film metallization system which can use thick film printed capacitors. Since the cost of thick film printed capacitors is approximately 10 percent of discrete capacitors, the thick film gold system was chosen as the baseline.

TECHNIQUE	ADHESION 1 x 10 MIL STRAP	M.W. LOSS AT 5.4 GHz	CAPACITOR	ASSEMBLY	COMMENTS
THIN FILM Ni/Cr/Au	76 GMS	0.078	DISCRETE	BOND	
THIN FILM Ni/Cr/Cu	84 GMS	0.076	DISCRETE	BOND	
THICK FILM Cu	—	>0.2	DISCRETE	REFLOW	DROPPED – HIGH LOSS
THICK FILM Au	60-70 GMS	0.086	SCREEN	BOND	BASELINE – LOWEST COST
THICK FILM Pt/Ag	68 GMS	0.1	SCREEN	BOND	REQUIRES CONF. COATING
ELECTROPLATE Cu/Au	50 GMS	0.076	DISCRETE	BOND	
ELECTROPLATE Cu/Sn	—	0.076	DISCRETE	REFLOW	
DIFFUSION Bond	—	—	DISCRETE	REFLOW	DROPPED – POOR ADHESION

Figure 6

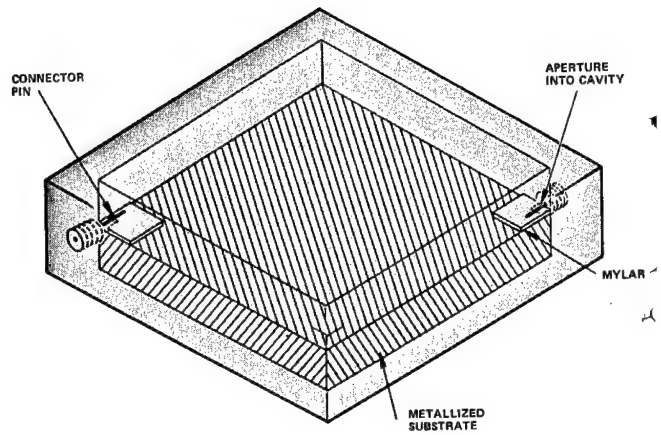


Figure 7

Dielectric Constant Critical Factor

Control of the substrate dielectric constant is important since it affects the electrical path length through the phase shifter. Two basic methods were used to test the dielectric constant. The first method used a cavity method and the second used microstrip ring circuits. The cavity method shown in Figure 7. It consists of a square piece of alumina metallized over all surfaces except for two small openings along two edges. The cavity method is useful for applications where the substrate is in the form of a square and has no holes in it. A sketch of the round microstrip resonant ring is shown in Figure 8. It consists of a microstrip ring printed on one side of the ceramic substrate with capacitive couplings at the input and output. This circuit is useful for substrates which are predominantly square and where the circular ring circuit avoids any holes in the substrate. Since the prepunched substrate is rectangular and contains a total of 29 holes, the "race track" shaped resonant ring circuit of Figure 9 was used. A circuit like this would be used in production to sample test incoming lots for dielectric constant.

Tolerance Effects On Performance

Calculations made on the effect of substrate thickness and dielectric constant tolerances on phase shifter performance indicate that the differential phase shift and insertion phase are most affected. The thickness and dielectric constant variations for most of the substrates are within ±1 mil and ±1 percent, respectively. A ±1 mil variation on thickness amounts to about ±4 degrees in insertion phase and about ±5 degrees on total differential phase. A ±1 percent variation in dielectric constant gives a ±4 degree change in insertion phase and ±1 degree in total differential phase. All these phase variations are considered within acceptable limits as far as the system is concerned.

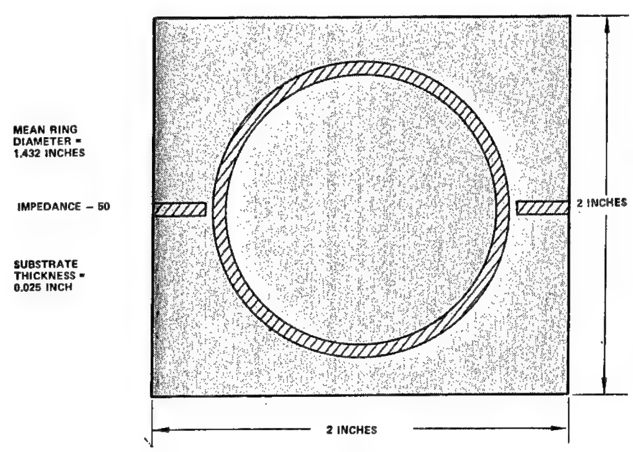


Figure 8

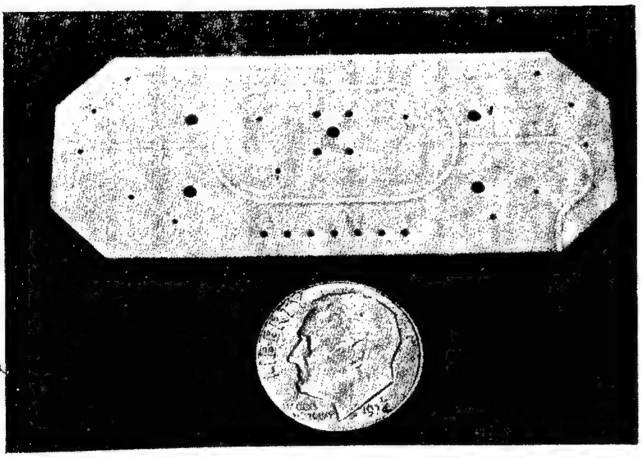


Figure 9

Phase Shifter Fabrication

The first manufacturing step during substrate metallization is deposition of gold in the inner ground plane area of the alumina substrate after a thorough cleaning step. All of the thick film materials are deposited by means of a semiautomatic screen printer, paste drying, and belt furnace firing. All of the thick film conductor materials used on this device are of the "fritless" type, which exhibit excellent microwave performance.

The front side conductor network and capacitors are deposited in the following sequence: network conductor—gold, dielectric—ceramic/glass, and top electrode conductor—gold. Next, the outer ground plane metallization is deposited. Platinum-silver was chosen for this application because of its superior performance during solder-attachment of the spring clip.

Use of the thick film metallization process made possible two unique features in this module: thick film capacitors, and effective substrate via metallization. The thick film capacitors replace conventional discrete chip components which require individual attachment to the substrate and wire interconnection. Thick film capacitors, in contrast, form a monolithic part of the alumina substrate (they are typically 0.002 inch in height) and require no loose wires or straps for interconnection. In addition, thick film capacitors typically withstand in excess of 500 volts before breakdown, compared to about 200 volts for MOS chip capacitors.

Substrate holes (vias) are formed in the alumina by prepunching in the "green" (unfired) state. This technique provides a great cost savings over traditional methods of substrate via formation such as ultrasonic or diamond drilling of fired alumina. Prepunched substrate vias have not been used extensively for microstrip applications due to the difficulty of metallizing the vias with thin film technology. Thick film printing, in contrast, accomodates such vias with no problem. Close control over the manufacture of the alumina substrates is required in order to use prepunched vias because of the well known variation in dimensional shrinkage of alumina during firing.

Phase Shifter Assembly

The phase shifter assembly involves mounting and interconnection of the diode chip as well as attachment of the contacts, spring clips, and radiators.

The diode chips are attached to the gold metallized substrate by use of Indalloy 2 solder. This solder was chosen because, unlike tin containing solders, it does not present a solubility problem with gold. The interconnection to the diode chip is made with gold strap which is welded to both the gold diode terminal and substrate metallization. The resulting monometallic bonds eliminate any potential problems due to intermediate effects.

The contacts and spring clips are reflow solder attached after pretinning. Radiators are attached with epoxy.

A number of important inprocess control steps are performed during phase shifter fabrication. One recurring control is visual inspection which is performed at both low and high magnification, under normal, oblique, and U. V. light conditions. The thick film capacitors are tested for leakage and capacitance; they are also screened at high voltage.

Diodes are tested, after mounting and interconnection, for leakage. In addition, all metallized vias are tested for resistance under high current conditions using a Kelvin measurement system.

Production Assembly

The assembly operations described were performed on an unbalanced prototype production line with considerable hand operation involved. For high rate production, a dedicated production line laid out as shown in Figure 10 would be used. Substrates would be metallized using a high speed printer. After printing and a drying cycle they would go directly to a furnace for firing. Next, solder for

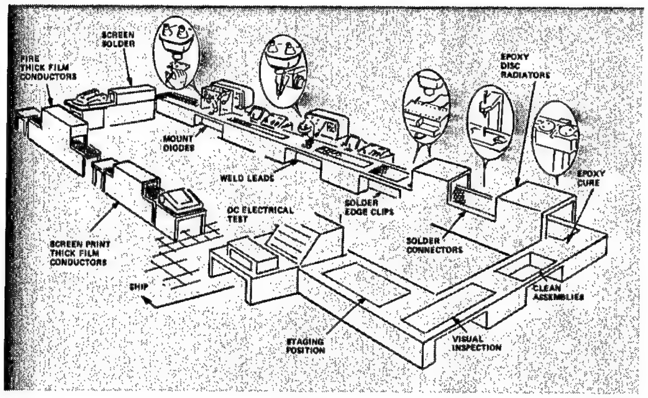


Figure 10

the diodes is screened in place. Diode attachment would be done by standard pick and place methods. Lead bonding for the diodes would be done at a manual welding station. Diode attachment and lead bonding could be semiautomated very easily, if necessary, for increased production rates. The edge clips are attached next using jigs in conjunction with a reflow solder station. The right angle transition is attached, again using a reflow solder process. The disc radiators are put on with epoxy to complete the assembly process. Following a cleaning operation and a visual inspection, the assemblies are given a final DC electrical test which completes the process.

In order to estimate the production costs for this dedicated production line, the fabrication process has been simplified and reduced to six major steps. Estimates of fabrication time for these steps are made on the basis of experience with the dual integrated substrates built during the MM&T program. The total production time per substrate is 1.497 hours. About half the total time is taken up with diode mounting and interconnection operations. Parallel bonding stations would be relatively easy to implement if higher thruputs are required of the production line.

Subarray Module Assembly

To minimize weight, cost and lengths of interconnecting electrical transmission lines, the module is organized in a sandwich concept consisting of subassemblies of the radiators/phase shifters, bias distribution board, and two 1:16 air stripline power dividers. The integrated disc radiators and phase shifter substrates are mounted on a die cast aluminum egg crate structure. This structure also permits RF isolation between pairs of phase shifters by providing an enclosed cavity behind each substrate. In the three modules built during the MM&T program, DC connection between the substrate and bias distribution board was accomplished by beryllium copper springs positioned between the two subassemblies. RF connection between the phase shifter substrate and stripline power dividers is accomplished by a short rigid coaxial cable attached to the stripline boards. A special coaxial to microstrip connector soldered into the phase shifter assembly completes the RF connection. In the event of a malfunction or to obtain experimental data, a phase shifter can be easily replaced by removing four screws located at the corners of the substrate.

Bias Distribution Board

The bias distribution board is used to route the control signals from the drivers to the phase shifters. A front and back view of the board is shown in Figure 11. The board is made from 1/16'' thick epoxy glass which is gold plated over the copper etched circuit. The gold plating will be replaced by tin plating with conformal coating for production boards. The 192 control lines from the drivers are brought in through six connectors which are soldered to the board. The control lines are then routed to each of the 64 phase shifter locations. A ground plane is provided

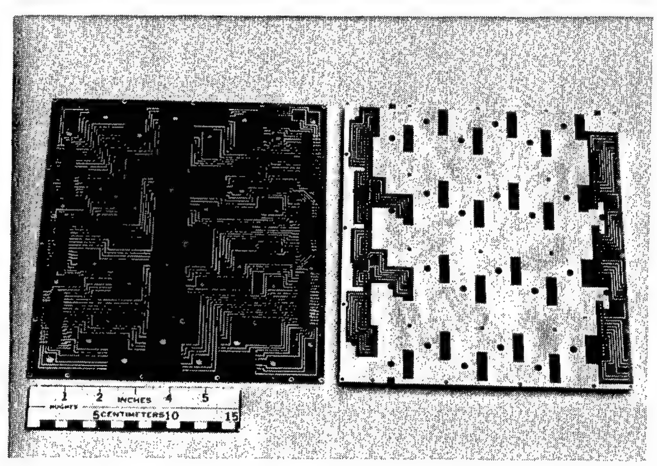


Figure 11

under each control line in order to minimize cross coupling during switching. Contact between the bias distribution board and the phase shifter was made with small coil springs in the three modules built on the MM&T program. In higher rate production these springs would be replaced with flexible ribbon leads which will be soldered at both ends during assembly.

Air Stripline Corporate Feed

The air stripline corporate feed assembly is a 2 to 32 power divider network which is made up from two pre-assembled 1 to 16 power divider assemblies. Figure 12 is a photograph of this corporate feed assembly.

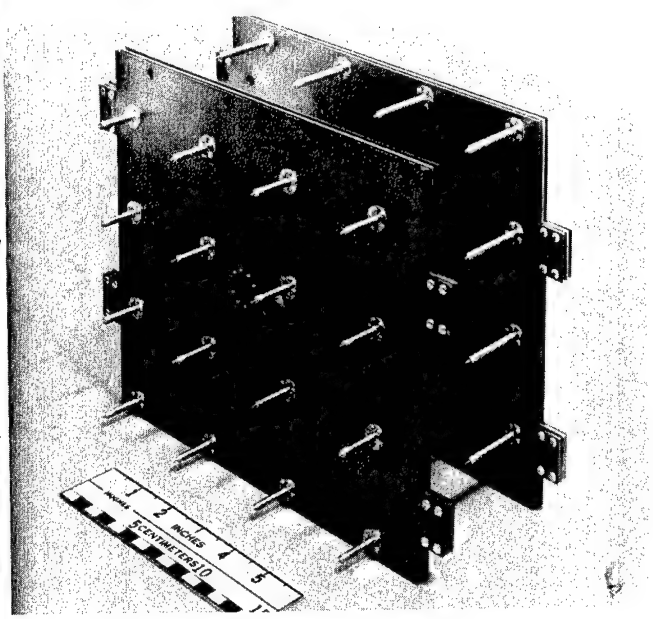


Figure 12

Each of the 1 to 16 power divider assemblies is made up of 1/32 inch thick aluminum ground planes, one 1/16 inch thick etched copper clad teflon fiberglass circuit board, one TNC input coax connector, sixteen output coax terminals, 32 dielectric ground plane spacers, and 32 rubberized block loads. Copper clad teflon fiberglass was selected as the circuit board material for its thermal expansion coefficient more nearly matches that of the aluminum ground planes than does any other available material. The RF circuitry on each circuit board is etched using the same set of negatives, which insures that all circuit boards will be alike. All of the holes in each ground plane, as well as the holes in each circuit board, are drilled by numeric tape control utilizing the same tape. Misalignment of holes during the assembly operation is virtually eliminated by this method. In high production all holes can be punched in one operation.

The assembly of each of the 1 to 16 power dividers is accomplished with the aid of a master alignment tool which precisely locates the position of each of the output coax terminals. Soldering of all output coax inner conductors to the etched circuit board circuitry is performed at this time. The entire power divider is riveted together into the final assembly before being removed from the master alignment tool.

Upon removal from the alignment tool, two of the 1 to 16 power dividers, an aft and a forward type, are attached together by means of mounting studs and spacers to make up the 2 to 32 air stripline corporate feed assembly.

Production Costs Summary

The production costs of the subarray module based on a quantity of 125 systems are shown in Table I. This assumes a fabrication time of 1.497 hours per substrate. The cost of making two modules on the unbalanced production line was $13K each.

In order to implement the captive production line described earlier, certain capital expenditures are required. The major production facility items cost $160,400.

Table 2 lists certain expendable tooling and periodically recurring expenditures which would be required during the total production run.

Item Description	Quantity	Est. Cost
Phase shifter and radiator	32	$1,132.48
Per unit		
Material $29.40		
Labor 5.99*		
Air stripline power divider (1:32)	2	485.60
Bias distribution board	1	57.20
Subarray module housing	1	142.62
Miscellaneous hardware		109.20
Total		$1,927.10
Cost per element of array module (including radiator, phase shifter and feed network)		30.11
Cost per radiator/phase shifter combination		17.69
Miscellaneous includes		
Compression spring bias contact		
Bias connector for housing		
Spring contact for gound plane		
Laminated shims		
Other hardware		
*Based on industry unburdened rate of $4.00/hour.		

Table 1

Item	Cost	Replacement Cycle
Thick film screen sets	350/set	Every 8K substrates
Process checks for thick film inks	4,100	Every 2500 substrates
Punch dies for substrates	2,060	Every 10K substrates

Table 2

Measured Results: Phase Shifter and Radiator Elements

Module One. Thirty-four phase shifter elements were fabricated and measured. The elements were measured by plugging into a waveguide test fixture. Each radiator was terminated into its own individual waveguide. Figures 13 and 14 show the measured results on a typical element. The phase shift is shown in Figure 13 for the three major steps. Figure 14 shows the input VSWR and the insertion loss for the unit. The average VSWR is about 1.5 over the frequency band. The insertion loss represents the variation among all eight steps over the frequency band. For all 68 elements measured at midband, the mean value is 1.45 dB with a standard deviation of less than 7 degrees.

Modules Two and Three. In general, the performance of the phase shifter and radiator elements in modules 2 and 3 compare favorably with module 1. The average insertion loss for modules 2 and 3 is about 0.15 dB higher than module 1. This is due to the PIN diodes which were made with lower resistivity, hence had higher RF resistance and more insertion loss. The phase for all three modules was nearly identical.

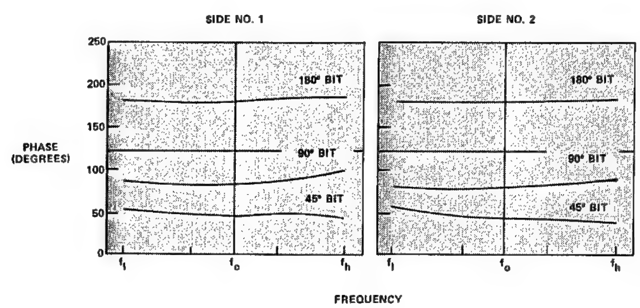


Figure 13

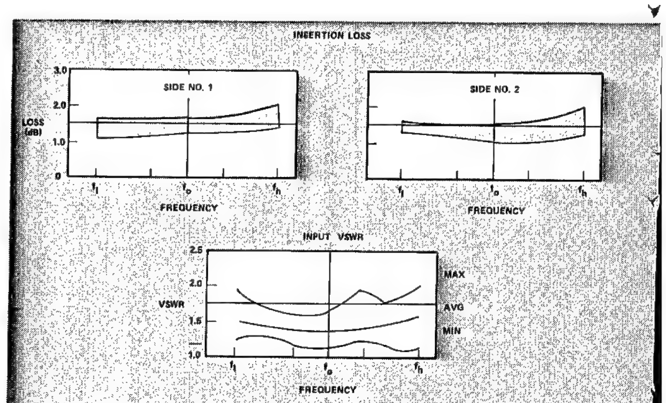


Figure 14

Results: Modules

Electrical measurements on all three subarray modules confirmed the integrity of the module design. The first air stripline corporate feed constructed provided equal amplitude and phase outputs to within 8.2 degrees rms and 0.36 dB rms. The second and third module feed outputs were found to be within 2.8 degrees rms and 3.6 degrees rms on each one. Total loss for each feed was 0.4 dB, 0.4 dB, and 0.5 dB, respectively.

Return loss measurements were taken on each module as a function of scan angle and frequency. The hybrid coupler that was used to feed the dual inputs of each module was found to be mismatched, which shows up as a cyclic variation in module VSWR as the aperture mismatch beats with the input hybrid mismatch. This mismatch will be reduced by improving the match of the 1:2 input hybrid. Each module was successfully power tested at various scan angles for a period of one hour or more at each angle. Peak power testing was done at 13 kW with a 40 microsecond pulse width at a duty factor of 0.01. Average power testing was done at 3.7 kW peak with a 50 microsecond pulse at a duty factor of 0.14. Peak and average power tests were performed separately since there was not a power source available to accomplish this at the rated peak and average power levels.

Subarray patterns were taken on each of the three modules and were found to agree closely with calculated patterns for this subarray. There was also good agreement between the patterns of each subarray module. These patterns were taken at various scan angles up to ± 60 degree scan and at several frequencies across the operating band, and all patterns were in good agreement with predicted values for no error cases. Axial ratio measurements were recorded along with each subarray pattern and found to be greater than 40 dB in most cases. There were a few scan angles that had axial ratios of 28 dB, which were the lowest recorded. The good axial ratio measurements were consistent across the operating band and scan coverage for each of the three modules that were fabricated.

The module design goals and measured values were as follows:

Environmental Tests

The "Integrated Subarray Module" was subjected to thermal, shock, and vibration tests. At the conclusion of each of these environmental tests the subarray was evaluated to determine if any mechanical or electrical failures had occurred. The diode bias levels were probed at each diode test point to determine if all bias signals were present and if all diodes were operating normally. These static tests indicated that all diode circuits were operating normally. Dynamic testing was also performed after each environmental test to establish that there was no degradation of the subarray patterns. No degradation of any of the subarray pattern was observed.

Production Test Procedure

The Hughes Aircraft Company views the 64 element subarray module as the smallest replaceable unit in the antenna. Automatic DC continuity tests are made on each individual substrate before assembly into the subarray module. RF production testing is only done at the module level, not on each individual component as has been done in the past.

In this MM&T program the module test was done by summing the measured performance of the air stripline feed and the measured performance of each phase shifter and radiator element. This was followed by pattern tests on the assembled modules. For production a special eggcrate module test fixture will be designed and built that will mate exactly with the aperture of the module. The eggcrate test fixture will consist of a matrix of dielectric loaded square waveguides, open at one face and terminated in coaxial probes at the opposite end. Ferrite isolators could be incorporated into each square waveguide, if needed. On the aperture end of the test fixture spring contacts will be attached which will mate up to the ground plane of the module under test. This will provide electrical isolation between all 64 disc radiators. Matching structures will be incorporated into the test fixture in order to provide a good impedance match between the disc radiator and the test fixture. This technique was done during the MM&T program where a dual aperture test fixture was built to measure phase shifter and radiator elements.

The test fixture will be used to sequentially measure the amplitude and phase of each element in the module as the phase shifters are stepped through the basic phase states. This data would then be summed to give the overall amplitude and phase response for the module. Go-no-go limits would be set on the automatic network analyzer to print out of bound elements. Rejected modules would then be sent back to the assembly area for further diagnostic tests and rework.

IR Tests Aid PC Boards

Effective Assembly Line Tool

Thermal imaging techniques, or infrared (IR), can be used to test printed circuit boards and hybrid microcircuits effectively at the assembly line level, a Hughes Aircraft Company study shows. There are at least four major types of electronic thermal testing:

- Design Verification—performed on newly designed electronic assemblies to locate potential sources of failure due to excessive component heat dissipation
- Quality Assurance—to prove that an electronic assembly is performing within thermal specification limits
- Functional—to demonstrate that an electronic assembly is operational
- Fault Isolation—to locate the faulty electronic assembly, circuits, or components.

The IR test system developed for the Missile Command under a Manufacturing Methods and Technology Program consists of an IR imager with closeup lens, a digital image processor, and a computer. The computer software and IR test methodology were developed to reduce PCB test time and simultaneously improve test efficiency.

Test results detailing the IR techniques have been consistently positive. Thermal evaluation of the quality of PCB plated through holes is possible, and the design of PCB heat sinks has been demonstrated as a natural application of IR testing.

GORDON D. LITTLE is an Electronic Engineer in the Engineering Directorate of the U. S. Army Missile Command, where he currently is Project Manager on the Department of Defense's Electronics Computer Assisted Manufacturing (ECAM) program, a recently initiated effort similar to the Air Force ICAM project. This forerunner program is being steered by an MTAG working group comprised of the Subcommittees on Electronics and CAD/CAM. The first phase of this broad based program is scheduled for 18 months of duration. Prior to this assignment, Mr. Little conducted developmental work after joining MICOM in 1971 in automated testing, microelectronics, automated test equipment, and packaging and design of a digital automatic pilot. Prior to his work at MICOM, he spent 12 years with Westinghouse, Sperry, and AMF Corp. He received his B.S. in Electrical Engineering in 1958 from Auburn University and his M.S. in Electrical Engineering in 1971 from The University of Alabama at Huntsville. He is a member of the International Society for Hybrid Microelectronics and serves as Chairman of the MTAG Working Group on Components and Packaging, a part of the Electronics Subcommittee of MTAG.

Secondary program objectives included the development of the necessary test equipment to perform IR testing, the formulation of IR testing methodologies, and the construction of data processing techniques and procedures.

IR Test System

The IR imager, a scanning thermal radiometer, feeds thermal image information about the unit under test (UUT) in the form of analog voltage signals to the digital imager processor. This analog image is produced at slower than TV rates—about 1.5 seconds per frame. The IR test system block diagram is presented in Figure 1.

The digital image processor converts the IR imager detector output from an analog to a digital signal format and performs simple arithmetic operations on images. These operations include summing, averaging, and subtraction. The unit provides digital image data to the computer for further processing. Finally, it converts the processed digital image data into a display at TV rate. This display is presented on the IR imager and a TV monitor. The digital image processor functional block diagram is presented in Figure 2.

The computer reads the digital image data from the digital image processor video memory and performs sophisticated arithmetic operations on thermal images. These operations include the computation of a standard temperature profile (STP), alignment of UUTs, out of tolerance computations, and displays and reports including a hard copy go-no-go map with coordinates. The computer also provides a permanent memory capability for STP storage and limited record keeping on floppy disks.

A box of clear acrylic plastic encloses the mounting fixture and UUT in order to eliminate the effects of sources in the background. The box has access ports for UUTs and cabling and permits visibility of the UUT while blocking IR radiation in the 8-12 micrometer spectral region where the IR imager is sensitive.

Test System Performance

The major equipment specifications when used with and without the closeup lens are presented in Table 1. Slight vignetting and transmission losses account for the poorer MRT when the closeup lens is installed. The IR imager spatial resolution is improved from 0.022 to 0.004 inch when using the closeup lens. This is adequate to permit the testing of most hybrids, when it is realized that it is usually sufficient to locate the region of a fault.

The field of view (FOV) with the closeup lens is 1.1 inches in diameter, which is just large enough to image a one inch square hybrid without requiring thermal scans at two positions. The frame refresh time is normally two seconds at 512 lines resolution, but can be decreased to one second at 256 lines resolution. The typical test time for a UUT scan is five minutes. Test times on PCBs and hybrids vary from six to 60 minutes depending on the IR testing complexity of the UUT.

Work on thermal testing of hybrid bonding quality for components and substrates has proven very effective. The backside of hybrids has given useful information on bad chips and faulty bonds. To be effective, these tests require power on times under ten seconds and components of relatively high power dissipation.

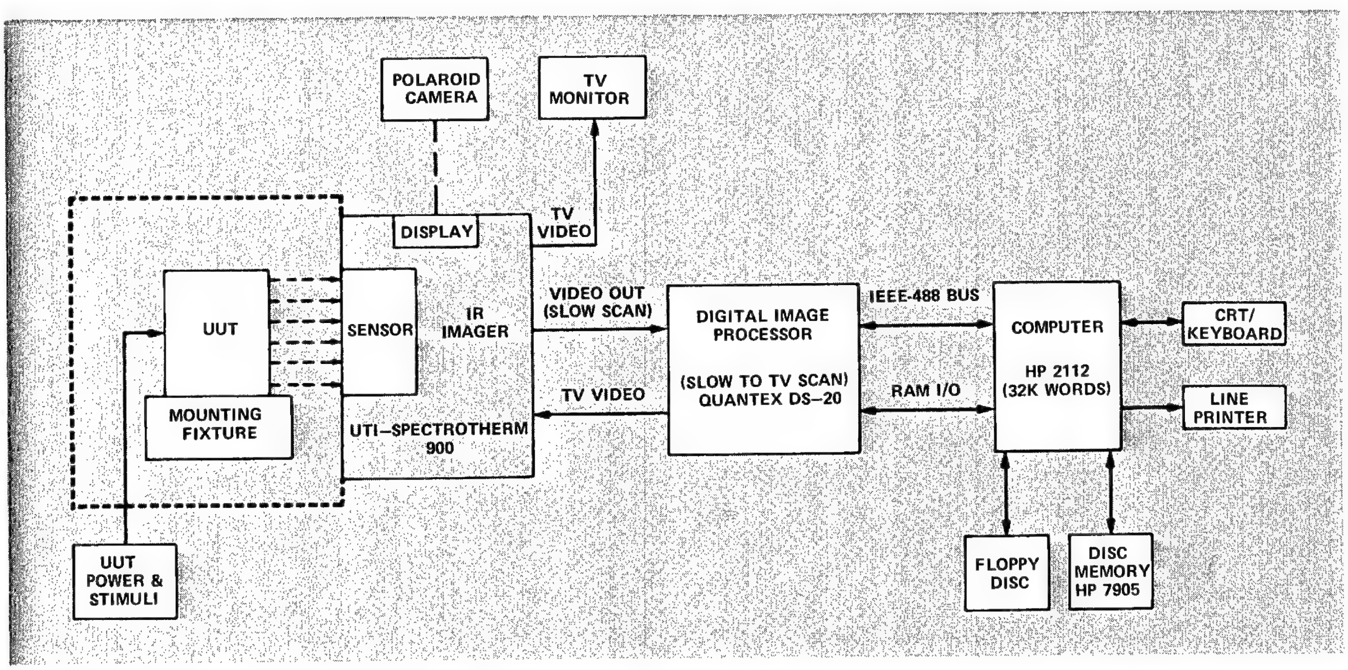


Figure 1

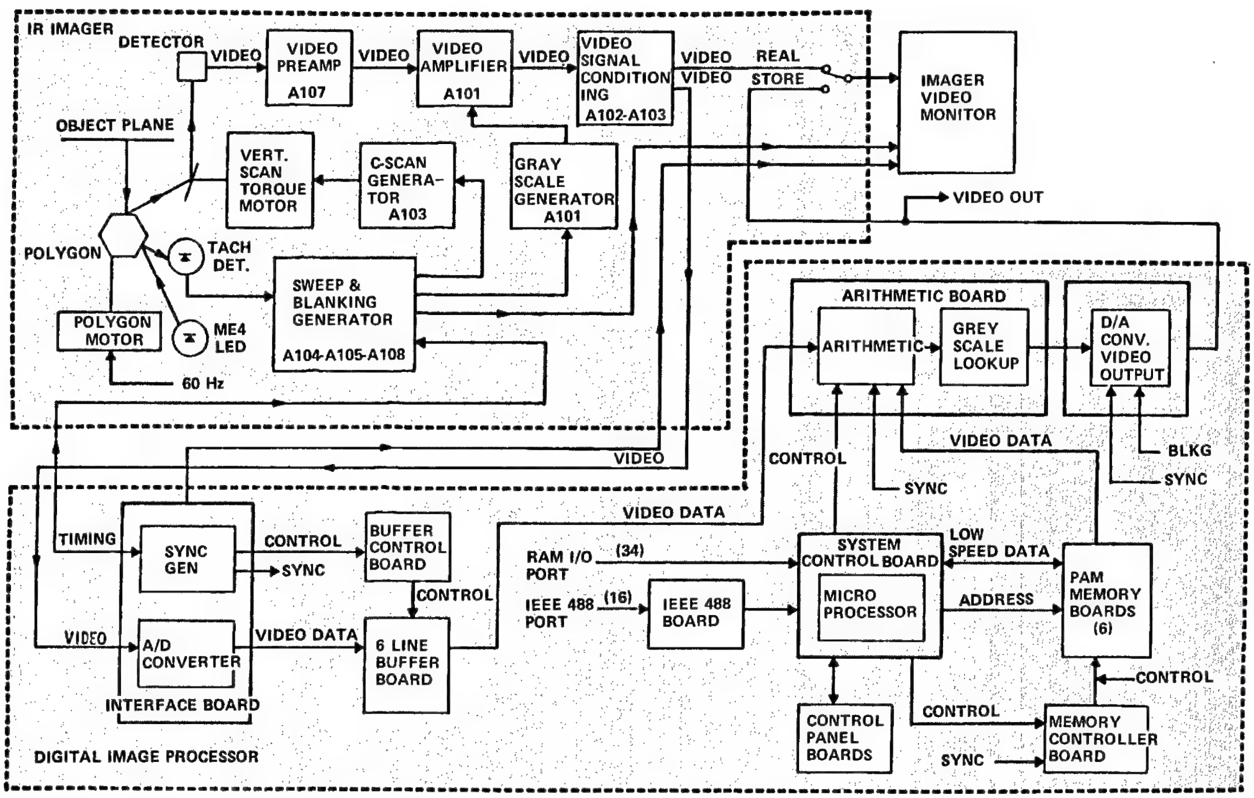


Figure 2

Equipment Specifications		
	WITHOUT CLOSEUP LENS	WITH LENS
• Minimum Black to White Temperature	2.0 C	2.0 C
• Minimum Resolvable Temperature, MRT	0.15 C(1)*	0.2 C(2)**
• Display Image Quality	512 lines	512 lines
• Spatial Resolution	0.022 inch(3)+	0.004 inch
• Field of View	6W x 4.5H inch(4)†	1.1 inch diam
• Frame Refresh Time	1 sec	1 sec
• Typical PCB/Hybrid Test Time	5 min	5 min
• Spectral Bandpass	7.5-14 micrometer	8-13.5 micrometer

Notes:

*(1) At 6″ before camera and object 0.050″ min diam
**(2) For object 0.020″ minimum dimension
+(3) At the camera front panel
†(4) At 6 inches before camera front panel

Table 1

Thermal testing efforts on plated through holes showed that a complete open can be easily discovered and that 20 percent voids in plate through cross sectional area is promising whereas less than 20 percent void in plate through cross sectional area is not detectable unless shorter test times can be achieved.

General IR Test Methodology

The IR test methodology covers three basic areas:

- UUTsetup, power, and stimuli
- Thermal imager and digital image processor operation
- Computer programs and operation.

The methodology for IR testing is developed so that the operating tasks are distributed between the operator, computer, and thermograph utilizing the best features of each. For example, the computer is used for the repetitive processing of large amounts of data while the operator uses the reduced data and his technical expertise to

deduce the failed component. The development of the IR methodology is based on the following guidelines:

(1) The test uses experimentally observed thermal data from proven UUTs for a baseline rather than theoretically computed thermal data.

(2) The data is processed so that the primary data given the operator is exception data (data that is outside the bounds of normal UUTs).

(3) The methodology minimizes unique programming for each UUT.

(4) The standard operating program is interactive, using comments on the terminal to direct the operator.

(5) A compressed thermographic image is used for most testing. The data compression is accomplished by averaging a square array of eight pixels per side (64 total). Thus, the original 512 X 512 (262,144) pixel display is compressed into a 64 X 64 (4,096) compressed pixel display. (This represents 1/8 inch resolution for an eight inch PCB).

(6) A modular set of programs is provided to permit the operator to vary the depth of the analysis as required by the particular UUT being tested.

Test Procedure Highlights

When the computer operator enters the program the machine will display the following message on the terminal:

PLEASE ENTER YOUR OPTION CHOICE:

1. Record PCB Thermogram
2. Compute PCB Composite
3. Test PCB
4. Display PCB Thermogram
5. Record Compressed Thermogram
6. Compute Compressed STP
7. Test Compressed
8. Display Compressed Thermogram
9. Alignment Test
10. Tolerance Change
11. Terminate Program

Options 1 through 4 and Option 9 utilize the full 512 X 512 display of the imager. Options 6 through 8 and Option 10 compress the display to 64 X 64 pixels.

Typical Test Procedure

The following typical test procedure is designed to detect faults on a UUT type that already has an STP on a floppy disk (a standard floppy disk is shown in Figure 3). The operator proceeds as follows:

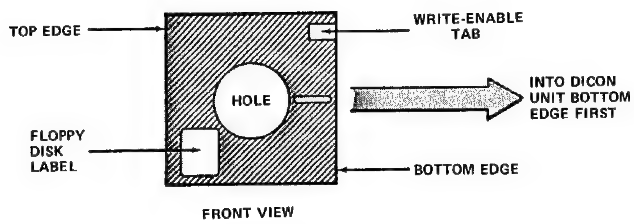


Figure 3

1. Enters Option 9 on the terminal.
2. The computer then directs him in a series of operations that make sure that the UUT is properly aligned.
3. At the conclusion of the alignment the operator enters Option 7.
4. The computer then obtains a compressed thermogram of the UUT. It subtracts the STP from the compressed thermogram and compares the difference with the tolerance matrix. The results of this comparison are displayed as an image of the UUT with abnormally hot areas shown in white and abnormally cool areas shown in black. Areas within the temperature tolerance are gray.
5. In most cases, the operator can deduce the failed component from this image and his knowledge of the UUT.
6. If additional analysis is required, the operator may obtain a hard copy printout of the compared data with hot areas indicated with + signs and cold areas with - signs. In addition, he may obtain a readout of the amount that temperatures are out of tolerance or a display of the actual temperature for specific compressed pixels.
7. The 512 X 512 programs of Options 1 through 4 are designed for detailed thermographic analysis. They may also be useful for problem UUTs.

Standard Thermal Profile(STP)

The test methodology is based on experimentally observed thermal data from proven UUTs. This data is initially obtained as follows:

1. The operator enters Option 5 on the terminal.
2. The computer then obtains and records a compressed thermogram of the UUT.

3. The operator obtains additional compressed thermograms of this UUT type. These may be obtained at any time desired using either the same UUT or different ones.
4. When the data base is large enough (2-10 samples), the STP is computed using Option 6. The computer calculates and records the average value of each of the compressed pixels and a tolerance matrix containing the maximum and minimum observed values for each of these.
5. If desired, the tolerance matrix can be modified by the use of Option 10. This allows compensation for the emissivity variation between components.

Options 1 and 2 may be used to obtain an STP for the 512 X 512 (262,144) pixel array with eight bits per pixel. A compressed image is also used for fault analysis. The data compression is accomplished by averaging a square array of eight pixels per side (64 total). Thus, the original 512 X 512 display is compressed into a 64 X 64 (4,096) compressed pixel display. (This represents 1/8 inch resolution for an eight inch PCB). Before testing a UUT, the following thermograms will have been obtained and stored:

Reference Room Temperature Thermogram. This is a 512 X 512 pixel image made at room temperature.

Standard Thermal Profile (STP). This is a 512 X 512 pixel image. It is computed by averaging the thermograms of several valid UUTs.

Compressed STP. This is a 64 X 64 pixel image. It is computed by averaging the compressed thermograms of several valid UUTs.

Compressed Tolerance Matrix. This is a 64 X 64 matrix containing the maximum and minimum values for each of the compressed pixels of the compressed STP.

Application Software for 512 Image

The following programs utilizing a 512 X 512 image have been developed:

Record Thermogram
This program records a thermogram on a floppy disk. The thermogram is grabbed from 0 to 60 seconds after the operator inputs a start command to the computer. The operator manually sets up the camera and image processor. The program asks the operator for the following historical data which will be recorded on the floppy disk:

Date
Time
Operator
PCB Part Number
PCB Serial Number
Room Temperature
Image Time Delay
Scan Time
Sensitivity
Base Level
Comments

Align PCB
The present room temperature thermogram will be cancelled with the reference room temperature thermogram and the cancelled image displayed on the DIP. This is continually updated so the operator can align the PCB.

Compute Standard Temperature Profile (STP)
This program generates a composite STP of the thermal images of many good UUTs of different serial numbers but the same part number. The input is thermograms stored on floppy disks and the output is an averaged thermogram stored on a floppy disk.

Test PCB
This program obtains a cancelled thermogram of the UUT and records it on a floppy disk. The thermogram is grabbed from 0 to 60 seconds after the operator inputs a start command to the computer. It is cancelled by the computer, with an STP previously recorded on a floppy disk.

Display Thermogram
This program takes a thermogram on a floppy disk and displays it on the DIP. The identification data is presented on the terminal and an option is provided to allow the identification data to also be printed out.

Application Software for Compressed Image

The following programs utilizing a 64 X 64 compressed image have been developed:

Record Compressed Thermogram
This program records a compressed thermogram on a floppy disk. Data compression consists of taking a square array of 8 pixels per side (64 total) and averaging them. The thermogram is grabbed from 0 to 60 seconds after the operator inputs a start command to the computer. The operator manually sets up the camera and image processor. The program asks the operator for the following data which will be recorded on the floppy disk:

Date
Time
Operator
PCB Part Number
PCB Serial Number
Room Temperature
Image Time Delay
Scan Time
Sensitivity
Base Level
Comments

Compute Compressed STP

This program generates a composite compressed STP (64 X 64 = 4,096 pixels) from compressed thermograms of several good UUTs. In addition to computing the average value of each of the 4,096 pixels, a tolerance matrix containing the maximum and minimum values for each of the 4,096 pixels is computed. Both the STP and tolerance matrix are recorded on the floppy disk.

Test PCB

This is one of the major options in the program. Testing of a PCB is conducted as follows:

(1) The operator installs the PCB and sets up the tester.
(2) The operator starts the UUT test sequence.
(3) The thermogram is grabbed at the end of the previously set image time delay.
(4) The thermogram is compressed.
(5) The compressed thermogram is cancelled with the compressed STP, the cancelled image compared with the tolerance matrix, and the results displayed on the DIP as follows:
   (a) Cancelled, compressed pixels within the tolerance limits are displayed as gray (decimal 128).
   (b) Cancelled compressed pixels below the tolerance limit are displayed as black (0).
   (c) Cancelled compressed pixels above the tolerance limit are displayed as white (decimal 255).

Display Compressed Thermogram

This program takes compressed thermograms, expands them, and displays them on the IR Imager CRT. The identification data is presented on the terminal and an option is provided to allow the identification data to also be printed out.

Generate Report

At the operators discretion any of the following reports for the PCB test can be obtained on the CRT and/or the printer.

- A display with + for temperatures above tolerance, - for temperatures below tolerance, and no indication of temperatures within tolerance.
- A report giving the amount temperatures are out of tolerance. This is expressed in tenths of a degree. No indication for temperatures within tolerance.
- A display of the actual temperature for specific compressed pixels.

Sample Reports

A sample report, Type 1, is shown in Figure 4. The minus signs refer to pixels on the test that were colder than on the STP. The plus signs refer to pixels on the the test that were hotter than on the STP. Bland areas are within range.

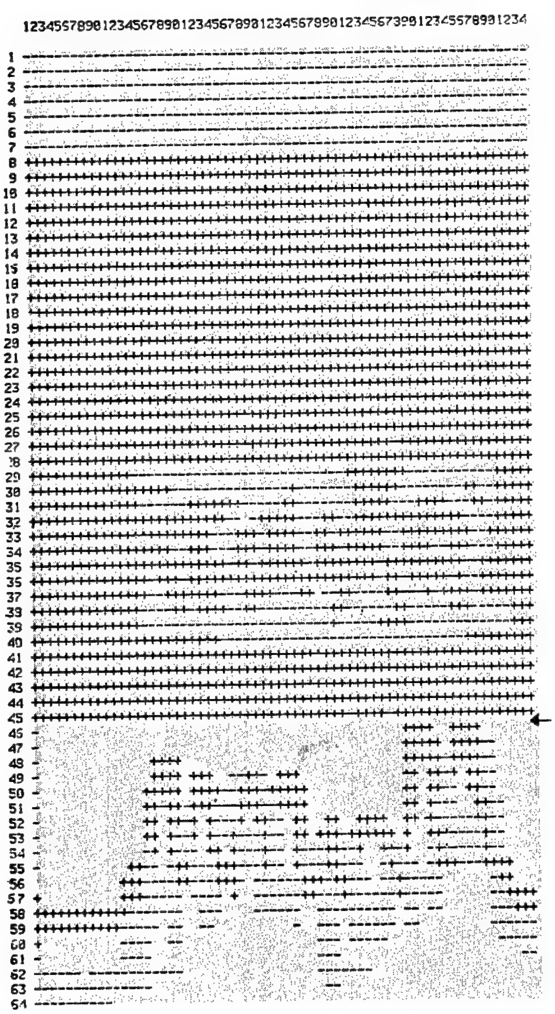


Figure 4

TEMPERATURE DIFFERENCE REPORT
EIGHT SECTIONS OF 8 X 64 PIXELS EACH

HISTORICAL DATA FILE

DATE: 00050 01090N0 0708
TIME: 00090 02060:0200
OPERATOR: R.N. BAGNER
PCB PART NUMBER: 3905802
PCB SERIAL NUMBER: 12
ROOM TEMPERATURE: 26C
IMAGE TIME DELAY: 10
SCAN TIME: 2
SENSITIVITY: 6
BASE LEVEL: 54

COMMENTS: COMPRESSED TEST AFTER CANCELLATION. POWER ON.

Figure 5

TEMPERATURE OF SPECIFIC PIXEL	
PIXEL (X, Y)	**TEMPERATURE IN C**
1,1	54.1
1,8	54.1
1,56	54.1
1,64	54.1
32,1	63.1
32,32	63.9
32,64	63.5
64,1	54.1
64,32	54.1
64,64	54.1

Figure 6

TABLE 2
Electrical Fault Detection

Items	Fault
Capacitor	Current leakage MTBF (short life) Reversed polarity Incorrect value
Chassis Assembly	Hot spots
Conductor	Nicks, voids Cold solder joints Fatigued wires Lifted lands
Conformal Coating	Pin holds, voids Scratches
Diode	Incorrect forward resistance Reversed polarity
False Circuit	Electrical noise Faulty component
Heat Sink	Poor thermal contact Poor design
Hybrid Circuit/Components	MTBF (short life) Inoperative TTL Gates Hidden flaws or cracks Absence of power supply inputs Chip to substrate bond quality
Operational Amplifier	Poor chip thermal bond Open circuit
Plated Through Holes	Missing plate through (open) Incomplete plate through
Resistor	Incorrect value Poor electrical contact Non-homogeneous composition
Resistor, Thin Film	Poor design Manufacturing resistance variations
Relay	Inoperable switch Missing drive power
Solder Joint	Voids Cold solder
Transformer	Open winding Shorted windings
Transistor	Thermal runaway Poor chip thermal bond Open circuit
Wirewrap Plane, Multilayer PCB	Short circuits

Table 2

A sample report, Type 2, is presented in Figure 5. This report gives the temperature difference in degrees centigrade between the STP and the UUT. Only those temperatures out of range are printed. The historical data file is given first.

A sample report, Type 3, is shown in Figure 6. The list varies in length, depending on how many pixels are desired.

The number of electrical faults that can be detected by the IR test system is still expanding at a high rate. A partial list is presented in Table 2.

WILLIAM S. CROWNOVER is a Research Aerospace Engineer with the Propulsion Directorate of the U. S. Army Missile Laboratory—part of the Army Missile Command. He currently is working on projects as for the past ten years concerned with low cost inert property components, including hardware, case, nozzle, and closure; also, manufacturing technology programs relative to propulsion. His fourteen years with MICOM prior to this were spent working on the inert components of rocket motors, following three years of work as a metallurgical engineer with Republic Steel. Mr. Crownover received his Bachelor Degree in Engineering from Youngstown State University in 1956. He is a member of ASM and the Association of the U. S. Army, and also works on the Tri-Service Subcommittee on Low Cost Solid Propellants.

Composite Mass Production Technique

Filament Winding of Rocket Motorcases

Small high performance rocket motorcases now can be mass produced quickly and economically utilizing a filament winding process, following completion of a three year manufacturing technology project conducted for the U. S. Army Missile Command. In addition to the greater speed and efficiency achieved, the filament winding process also proved itself very cost competitive with forging of high strength steels.

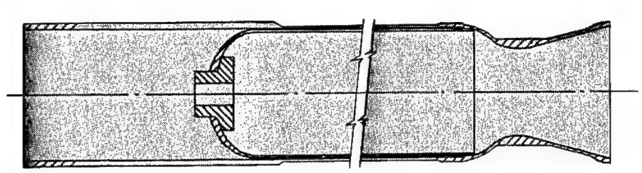
The goal of the program—carried out by the Hercules, Inc., Allegheny Ballistics Laboratory—was to establish mass production techniques for filament wound composite rocket motor components. The component studied was an integrated filament wound composite chamber and nozzle (CoCAN).

Two Designs Selected

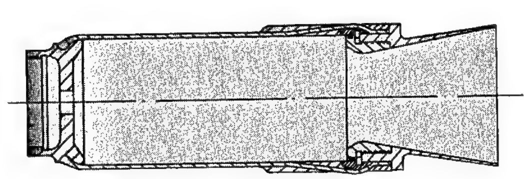
As a starting point for the study, two small rocket motorcase designs were selected, shown in Figure 1. One design was designated as the case in case design and the other as the one piece design. The case in case design consists of an inner shell which contains a cylindrical section with the forward dome. The outer shell contains a cylindrical section with an integrally wound nozzle and forward skirt. The two shells are slip fitted together and bonded after propellant loading. The one piece design consists of a large forward adapter, fiberglass cylinder, and attachable nozzle. Both designs have identical structural requirements and capabilities.

To establish the methodology, a base production rate of 10,000 units per month was selected and operations required for the manufacture of the two designs were identified. In an effort to improve these processes, a survey was made of processes in related industries. A cost/trade exercise then was performed on materials, equipment, and process. The results of the survey and trade studies were used to establish a mass production plan for each design. The equipment and process materials requirement—along with all associated costs—were developed for each design and formatted into cost trade charts.

Table 1 summarizes the direct labor hours and unburdened material costs for each design. The tooling was broken down into two categories (capital and special base) per the ASPR regulations. The hours and material cost have been projected to include overhead rates. The case in case unit price is in the $13 to $14 range and the one piece case in the $19 to $20 range; however, the individual plant and accounting system will affect these prices.



CASE IN CASE



ONE PIECE CASE

Figure 1

Table 1

	One Piece Case Manhours	Case in Case Manhours
Pre-Loading Operations		
Winding	0.016	0.048
Machine and Stripping	0.016	0.032
Mandrel Handling	0.040	0.072
QC	0.016	0.032
Other	0.056	0.082
Subtotal	0.144	0.266
Post-Loading Operations	0.008	0.048
Total	0.125	0.274
Materials		
Case	$ 4.43	$ 3.67
Nozzle	6.54	—
Other	0.39	1.20
	$11.36	$ 4.87

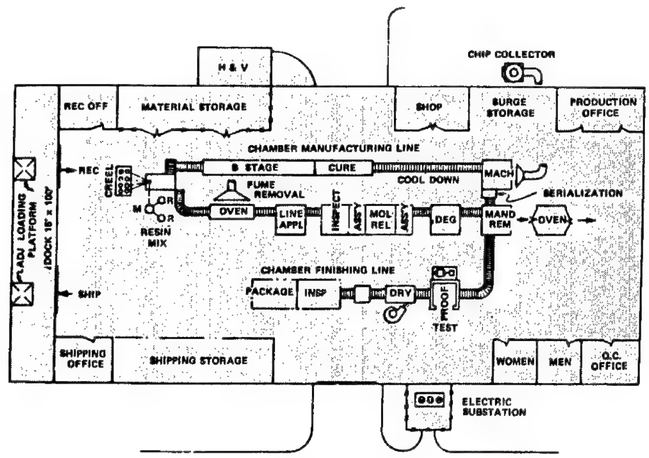


Figure 2

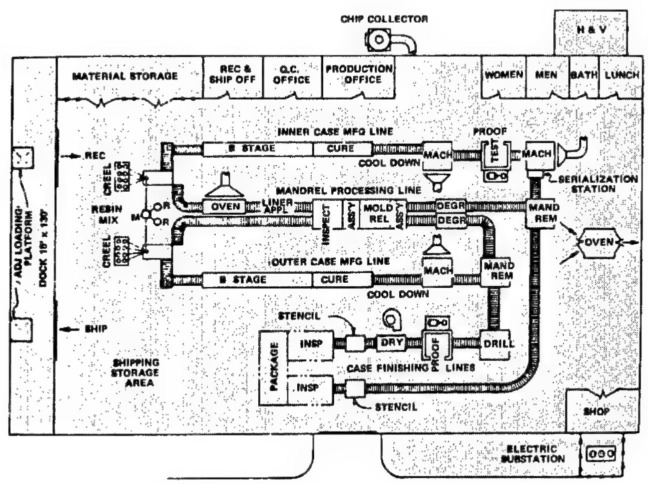


Figure 3

PRODUCTION LINE LAYOUT

The results of the costing exercise suggested the type of equipment and the method necessary to process the unit through the production line. The manufacturing line for the one piece design is shown in Figure 2 and that for the case in case design is shown in Figure 3. Since the lines for both designs are very similar, only the one piece case line will be described.

A supply of 36 end center pull S2 roving is placed on a typical creel behind the winding machine. Six 30 pound balls are fed to the resin impregnation cup and to the individual winding heads for the six double windings. The creel is basically a table with ceramic guide eyes to prevent roving tangles. The first guide eye must be located directly over the spool with a center pull system.

A demand type automated mixing system is located near the winding machine. The system has two reservoirs—one for the resin, Epon 826, and one for the catalyst hardener premix. The premix, CIBA 917 and BDMA, is blended with a high shear mixer; then the resin and premix are proportionally pumped (100 to 81 ppw) to a static mixer and deposited into the resin cup as required by the level control. The reservoir tanks are replenished once each shift.

Only one resin cup is used for the six windings. The resin level in the cup is controlled with a high low sensor which actuates the pumps of the resin mixing system. The roving is delivered wet from the cup to the winding head.

Six Units Wound Simultaneously

The winding machine winds six double units at a time. The roving delivery head is behind the spindle, providing the operator uninhibited access to the mandrels and winding at the front. The mandrels are set into the machine by hand and locked into place with an air cylinder. The first operation performed by the machine is to "tie" the roving onto the mandrel. The winding machine then winds the units, while being controlled with a mechanical cam for helical windings and lead screw for the hoops. Switching from hoop to helical windings is performed by the operator. This can be done without cutting the roving between hoop and helical layers. At the completion of winding, the operator removes the excess resin, cuts the roving, and installs the completed unit on a conveyor which leads to the cure oven.

The oven conveyor system transfers the wound units from the winding machine through cure and to the machin-

ing station. A two zone hot air oven is used for curing. The conveyor speed controls oven residence time for the B stage and final cure, during which the unit is rotated by drag wheels at the mandrel ends.

The unit is picked up manually and installed in the machining fixture. This fixture rotates the unit while two diamond tipped tool bits make plunge cuts to size the overall length of the unit. The end fittings, including the drag wheels, then are removed from the mandrel and placed in degreasing baskets. The mandrel then is manually installed in the stripping fixture.

Stripping Automated

At the mandrel stripping operation, the line divides, with the mandrels being sent back to the winding machine and the unit on to hydrotest. The two units and scrap are stripped from the mandrel with hydraulic cylinders. The stripping fixture has two cylinders, each of which strips one unit at a time along with the scrap. The scrap automatically falls into a holding bin, and the units are placed in a vertical position on the conveyor to the hydrotest station. The mandrel is placed in a basket for degreasing and cleaning.

The mandrel cleaning is performed in a standard solvent cleaning system. Six sets of mandrels and attachment hardware are placed in one cleaning basket. The basket is lowered into boiling solvent, then into cold solvent and finally allowed to stand in the vapor. This system removes any dust and contaminants that are soluble, such as hand grease. The basket then is moved by an overhead crane system which finally deposits the mandrels at the mold release station.

Mold release is performed in an enclosed spray area. The mandrels must have the end fitting temporarily installed to allow rotation. After the mandrels have been sprayed with mold release, the forward adapter, aft attachment ring, and plastic piece to protect the mandrel at machining must be installed. The mandrel then is moved to the mandrel inspection station.

From the time the mandrels enter the mandrel inspection station until delivery back to the winding machine, they are transported horizontally on a conveyor. The inspection of the mandrels is performed automatically. They are picked up by the inspection machine, rotated, and the diameter checked for tolerance and concentricities. Any out of tolerance will cause automatic mandrel removal from the line. This inspection operation is important because the mandrel controls the inside dimension of the case, and the inside of the case is not subsequently inspected.

Final Prep and Inspect

Final preparation of the mandrel involves application of the rubber liner. Polysulfide rubber was selected for the liner on the basis of cost. The rubber is premixed with a solvent and sprayed on the mandrel to a nominal thickness of five mils. After the spraying operation, the solvent must be removed and the rubber staged to a usable condition. The rubber coated mandrels pass through an oven to harden the rubber to prevent the winding from damaging the coating. After the rubber has been set, the prepared mandrels are deposited at the winding machine, ready for reuse. The final cure of the rubber will occur during chamber cure.

The hydrotest of the completed unit is performed in a vertical position. The unit is automatically positioned under the head of the hydrotest machine. A piston is automatically inserted in the aft end and the forward end is sealed. A shield is placed around the unit. This equipment leaves very little free volume in the case to enable rapid pressurization. The hydrotest proofs the case to simulated flight loads, including the aft adapter ring. Should a chamber fail in hydrotest, the machine automatically clears itself and receives the next unit. After hydrotest, the unit continues horizontally on the conveyor to the air dry station and on to the inspection station.

The cases are inspected dimensionally with automatic inspection equipment. All of the inspection dimensions are external and include outside diameters and lengths. Here again, any out of tolerance will cause rejection. After inspection, the unit continues on the conveyor to the package station.

The one piece case is packaged in a divided pasteboard carton containing 25 units. The carton is placed on a wooden pallet (30 cartons per pallet), banded, and labeled ready for shipment.

The only operation required to complete this unit is the nozzle installation. This is performed after the propellant has been loaded into the case. In this simple operation, the nozzle is slipped in place and a snap ring installed.

MANUFACTURING TECHNOLOGY DETAILED

The second year's program, Phase II, demonstrated the manufacturing technology identified in Phase I. This was accomplished by prototype development of the essential production techniques.

A case (shown in Figure 4) was designed to demonstrate the mass production techniques. The unit was designed to have a minimum burst pressure of 11,400 psi and a capability of 37,563 pounds thrust. This design was one result of the first year's study.

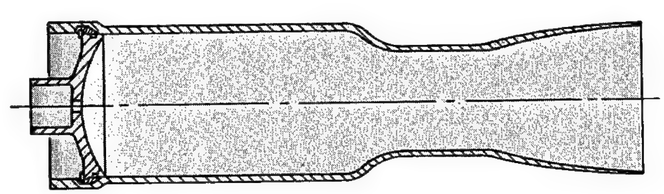


Figure 4

An existing winding machine was modified to handle two double windings simultaneously at a mandrel speed of 200 rpm. The 200 rpm corresponded to a roving speed of about 150 ft/min. A resin mixing and delivery system was purchased and modified to automatically deliver resin to the resin impregnation cup. The resin impregnation cup was designed to be stationary and use transfer wheels to impregnate the roving. Thirty six end center pull roving balls were used to allow high speed roving delivery.

Case machining was simulated by using a diamond tipped tool to cut tubes similar to the case wall construction. The ideal feed and speeds were determined. A mandrel reproducibility demonstration was performed using the selected mandrel production material. The results of these demonstrations and refinements are summarized in Table 2.

	Production Method From Phase I Study	Simulation Goal in Phase II	Actual Results
Winding Numbers	12 units at a time	4 units at a time	4 units at a time
Roving Speed	150 ft/min, 36 end	150 ft/min, 36 end	216 ft/min, 36 end
Roving Delivery	Wet	Wet	Wet
Resin Mixing and Delivery	Automatic	Automatic, capable of production	Automatic, capable of production
Case Machining	Diamond tipped tool 120 cuts/min, 1200 desirable	Cut rings simulating case wall	850 cuts with no sign of tool wear
Case Dimensional Stability (Mandrel Control of Dimensions)	Hold ±0.001 diameter and 0.002 TIR on case ID	±0.001 diameter and 0.002 TIR	All cases were in ±0.001 D and 0.002 TIR
Resin Impregnation	Transfer wheel	Transfer wheel	Transfer wheel

Table 2

Winding Equipment

To demonstrate the production techniques, several pieces of equipment had to be designed. These included a modification of an existing winding machine, a delivery head, resin cup, resin mixing and delivery system and wiper system. All items of equipment were identified at the start of the project with the exception of the wiper system. This became necessary when higher machine speeds were attempted and the resin was being thrown from the winding. All equipment was designed inhouse with the exception of the resin mixing equipment. Here, a commercial item was purchased and modified.

The base winding machine used for the demonstration was a standard ENTEC, Type 800 series, machine. The machine has three degrees of servodriven capability along with a 20 foot length capability. The design of the equipment for the winding machine followed the guidelines that the modification would

(1) Increase the basic machine speed from 100 rpm to 300 rpm

(2) Allow the double windings at a time

(3) Require the use of only one degree of servo control to wind the units

(4) Provide rapid installation and removal of mandrels.

Six An Efficient Number

The original study showed six double units must be wound at a time for an efficient production process. However, for a prototype demonstration, it was reasoned that two double units wound at a time would present the majority of problems expected with six.

The restriction of using only one programmed degree of freedom for the machine was an attempt to reduce the complexity required of the production winding equipment; ergo, lower initial and maintenance costs. The one degree used was horizontal carriage position; however, to maintain good pattern control, the winding head must be turned at the end of the helical stroke. This was accomplished with a mechanical device on the winding head.

The need for rapid mandrel installation and removal for low cost production is self evident. Approximately one minute was allotted for installation and one minute for removal of six mandrels from production equipment. The equipment was designed so that the mandrel assembly only need be set between two guide blocks on the winding machine. The guide blocks are set on a ramp that automatically positions the mandrel to be picked up by the idler and drive shafts. The idler shafts are actuated by air cylinders which make the final engagement with the machine. The removal of the mandrel is accomplished by actuating the air cylinder in the opposite direction and hand lifting the mandrels.

Resin Mixing

The first step in evaluating the resin mixing system was to determine that the positive displacement proportional pumps for resin and hardener delivered the correct mix ratio. To accurately determine the mix ratio, an analytical chemical procedure was used. The weight per epoxy equivalent for hand mixed resin at the ratios of 100/70, 100/81, and 100/90 was compared with the output of the mixing machine. The results agreed within the experimental accuracy of the test.

Once the mix ratio accuracy was verified, the next step in the evaluation was to determine if the system satisfactorily mixed the resin and hardener. This was evaluated by comparing tensile tests of neat resin samples from a hand mixed batch and a machine mixed batch. Twelve samples were tested from each mix. The hand mixed

resin yielded an average tensile strength of 12,462 psi and standard deviation of 1038 psi versus 11,794 psi with a standard deviation of 1566 psi. The results were considered to be satisfactory and the final evaluation was performed. This was to structurally test units that had been fabricated with hand mixed resin and machine mixed resin. The hand mixed units failed at an average pressure of 13,233 psi. The failure values were considered equal, thus verifying the acceptability of the resin mixing.

Resin Delivery

The evaluation performed on the resin delivery system was visual and occurred during the winding of cases. The only criteria used was its ability to provide sufficient resin to perform the windings. In every trial, the system performed satisfactorily; the system has sufficient capacity to wind six double units at a time.

Roving Impregnation

The only accurate way to evaluate resin impregnation is from a resin burnout test of the cured composite. Three locations were tested since the resin content was expected to show some variation with respect to the winding pattern. The values are typical for an all-helical winding. For a mixture of helicals and 90's, the structure is consolidated and results in lower resin content values (20-25 percent).

Winding

Initial evaluation of winding performance at low speeds, up to about 100 rpm, indicated a satisfactory helical winding pattern. However, as increasingly higher speeds were tried, difficulties in controlling the winding pattern occurred and were related to basic machine dynamics. Compensation was accomplished by modifying the control cams. The winding speed was ultimately increased to 285 rpm, yielding a roving speed of 216 feet per minute. This was 43 percent over the estimate made in the first phase of the program and will yield a lower production cost.

Machining

The evaluation of machining parameters was performed by using a diamond tipped tool bit to machine a helical wound cylinder, simulating the case wall. A feed rate of 0.0024 at 315 rpm was established as nearly optimum. After 300 cuts, there was no apparent wear on the tool bit. Since the upper acceptable feed and speed range had been found, the machining was continued until the manufactured tubes were exhausted. This occurred at the 881st cut. Examination of the tool bit under 30X microscope showed little sign of wear. Some very, very slight rounding of corners could be detected. It is difficult to predict the actual tool life; however, it appeared it will be over the original 1200 cut estimate. The time required to make the actual cuts, in production, will be about eight seconds. The original time estimate from the first phase was one minute per unit, including installation and removal. It now appears the entire cycle time would be less than 45 seconds.

Chamber Performance

The chamber performance was evaluated on weight, dimensional attributes and structural integrity.

Of 54 units checked, the weight varied from a low of 353 gm to a high of 399 gm. However, when the data are viewed in relationship to machine position and fabrication problems, it appears the standard deviation will be about nine gm for production. This is a coefficient of variation of 2.4 percent. The data showed no basic difference between the head stock and tail stock positions on the machine; however, there was a difference between the upper and lower positions. The wiper system was not fully developed when the early windings were performed. This caused additional resin to be deposited on the lower winding due to the drippage from the upper winding and wiper system. Therefore, one would expect to see a higher weight in the lower units. Since the wiper system is now fully developed, it is expected the lower units will weigh the same as the upper windings.

To evaluate dimensional stability of the units, they were measured directly after hydrotest and showed a high variation in the ID measurement, a spread of as much as 0.006 in. To verify the measurement, the units were measured about three weeks after the hydrotest. At this inspection the greatest variation in the dimensions of the units was only 0.002 in. There had been a physical dimensional change and the units were within the ± 0.001 tolerance range. There was, however, a growth of 0.0025 in. due to the hydrotest.

The final evaluation of the chamber was based on the structural integrity. Fourteen chambers were burst tested. All units failed by shearing out the fiberglass in front of the adapter. The average failure was 13,095 psi with a standard deviation of 577.6 psi. The results were slightly lower than anticipated, however, over the 11,400 psi minimum burst level. It was expected that the unit would fail in the 14,000 psi range.

The chambers satisfactorily met all the performance requirements. The only area considered not fully demonstrated was the ability of the units to maintain drawing tolerance after proof testing. Although the unit dimensional stability is projected as being acceptable with a mandrel dimensional change, more study is needed on this issue.

Mandrel Stripping Only Change

As a final overall evaluation, the original production estimates were compared with the results of this program (Table 3). The only change made in the original process

Table 3

	Original Estimate, Manhours	New Estimate, Manhours
Winding	16	12
Storage	2	2
Machining	4	4
Mandrel Removal	4	
Mandrel Cleaning	3.5	3.5
Mandrel Assembly	4	4
Mold Release	4	4
Liner Application	4	4
Hydrotest & QC	8	8
Materials Handling	8	8
Fill-in Man	8	8
	65.5	57.5
	8.19 Men	7.19 Men
	8	7

was the mandrel stripping operation, as it appeared that this operation should be combined with the machining operations. The resulting estimate was that seven operators could operate a line producing 500 units per day.

FINAL PROCESS REFINEMENTS

A satisfactory process had been established by the end of the second year, but there were some areas where refinements would improve and/or shorten the process. Four areas were selected for work:

- Winding time
- Resin impregnation
- Handling of excess resin
- Holding the adapter during winding.

Each of these areas was substantially improved.

The winding cycle time was reduced 30 percent. The resin impregnation system was improved for low delivery rate, control of quantity applied, and cleanability. A method was established for recycling excess resin, and an improved system was designed for holding the adapters.

Fabrication of Units

Over 300 units were fabricated during the program. The first units were used to evaluate changes in the process and new equipment. Once the process was established, 300 units were fabricated—the first 50 of these were made on the two mandrels left over from the second year program. The remaining units were fabricated on new mandrels. This allowed the winding of 32 units a day.

The method of fabrication was basically identical to that used during the second year effort. The mandrels were prepared by applying a liquid mold release and installing the adapters. They were then installed in the modified winding machine, two at a time. Four spools of twelve end S2 glass rovings were fed through the resin impregnation system and delivery head and tied on the mandrel. This was the last time the operator touched the roving until the unit was removed from the machine. The first portion of the winding was a 90 degree fill around the adapters. The winding pattern is shown in Figure 5.

The fill location was controlled from a constant horizontal feed with a revolution counter. The 90 degree fill was completed at the center of the mandrel. The machine was changed from a level wind to helix mode. The complete helix pattern was completed after 2035 revolutions of the mandrels winding at 350 rpm. This took 5.8 minutes to complete the helical winding. After the helix was completed, the machine was turned to the level wind mode and the hoop overwrap was completed.

The units were then placed in a rotating fixture and cured. The parting cuts to remove the units from the mandrels were also the final machine cuts. The only operation performed after the mandrel removal was to hydrotest the units to 7000 psi.

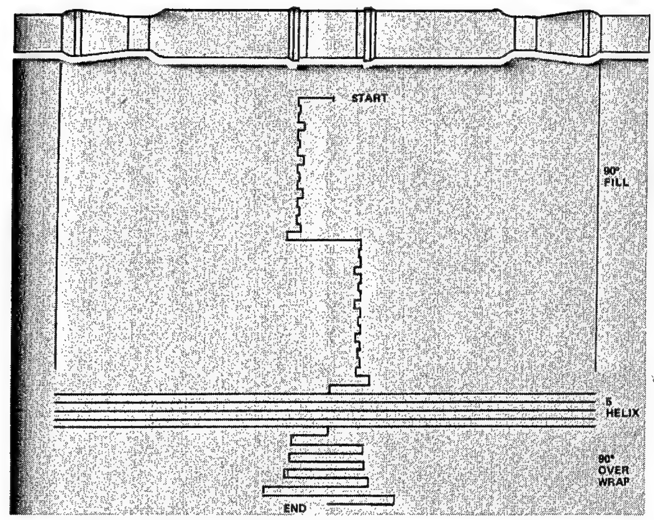


Figure 5

Testing

The destruct testing performed on the program was in the form of burst tests. The nondestruct testing was in the form of a proof pressure test. Both tests were performed on that same hardware. In all, over 300 units were proof tested and 25 units burst tested on the hardware. The equipment is capable of a pressure of 15,000 psi, which was the maximum available to burst test units.

POSTTEST EVALUATION

An attempt was made to develop a posttest mechanical and material evaluation test. The objective was to be able to predict strength levels of units after hydrotest. Two approaches were used; ultrasonic testing after hydrotest and acoustic impact testing.

The majority of unit failures occurred by shearing out the adapter. Ultrasonic testing was considered a possible means to detect incipient failure resulting from the proof test.

The equipment chosen for the ultrasonic inspection effort was the Fokker Bond Tester. To be correctly used, the equipment must be set up and calibrated with samples of material which simulate the thickness of the case. The equipment is set up and zeroed using the actual wall thickness. A second standard is used to define the effect on the signal of a thinner sample. This would indicate separation between the ID and OD. A coupling fluid is used to provide a good connection between the probe and the samples or case.

A total of 33 cases were inspected utilizing the technique. They were inspected by rotating the cases and sliding the probe in a circumferential direction and then moving in increments along the length of the case until the entire length had been inspected. In all instances, the Fokker Bond display moved to the left of zero indicating no interference with the signal through the thickness. This showed no voids or delaminations existed. Following this test, the cases were then subjected to a proof test. The cases were then reinspected using the same technique as before. A comparison of the data for the pre- and posthydrotest inspections indicated little or no change as a result of the pressurization. Three units which showed the greatest changes were burst. In each case the units failed above the average pressure of all units tested. Based on the results, it has been concluded the method was ineffective.

Acoustical response was explored as a posthydrotest evaluation. The initial work was not able to predict strength level. The method was based on observing the change in dominate frequencies before and after hydrotest. Another approach was then used. This was to determine at what pressure the dominate frequency changed. The results of this effort were also inconclusive.

Vibrations Analyzed

The acoustical vibrations were generated by striking each unit with a calibrated blow. It was theorized that filament wound fiberglass units fabricated under a controlled condition would have the same acoustical properties. To test the theory, virgin units (not hydrotested) were suspended on a fine wire and struck a uniform blow. The acoustical vibrations were then recorded and analyzed. A schematic, and photograph, of the test setup are presented in Figures 6 and 7. The analysis of the vibration took two forms: reading individual natural

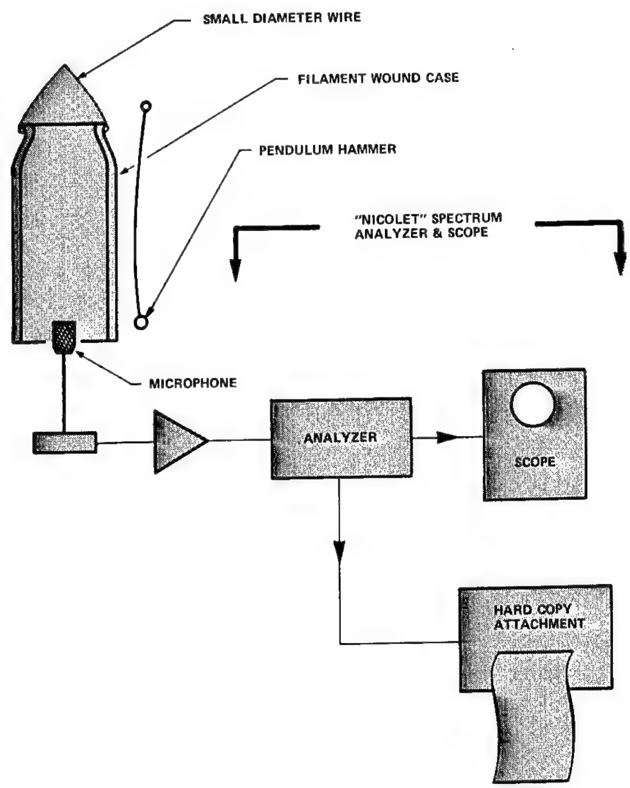


Figure 6

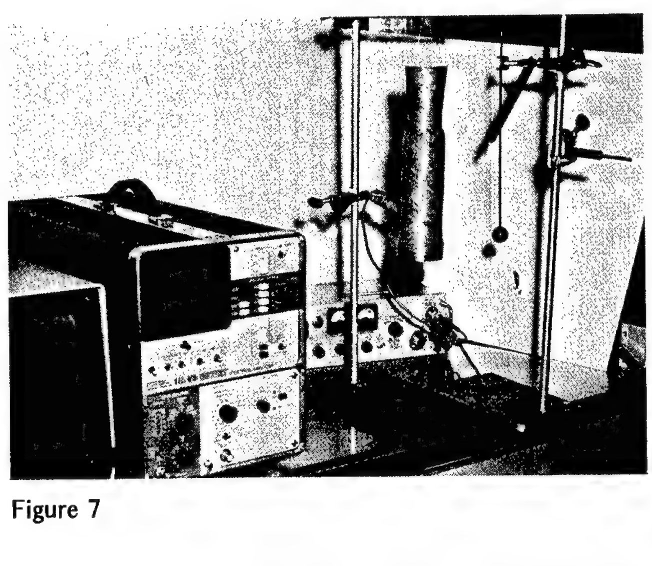


Figure 7

frequencies and comparing damping characteristics of the signal. This is done by capturing 0.08 sec of sound signal emitted from the unit after being struck with a pendulum. The recording and analysis was done on a Nicolet 440A Mini-ubiquitous Spectrum Analyzer. Examples of a typical frequency spectrum and a real time transient wave form are shown in Figures 8 and 9.

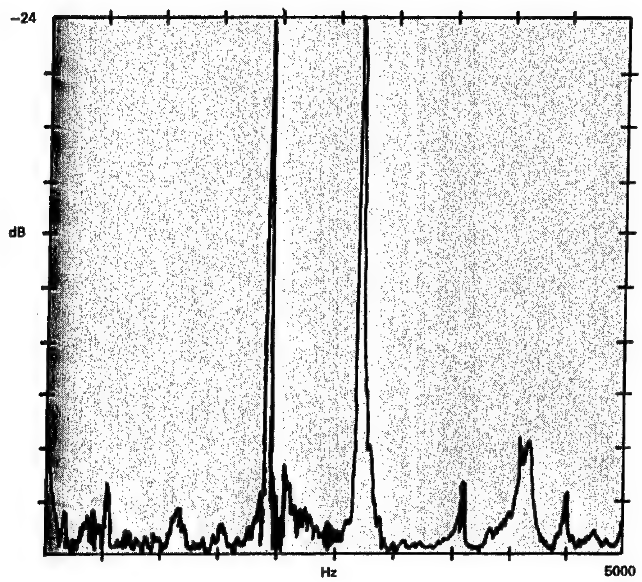


Figure 8

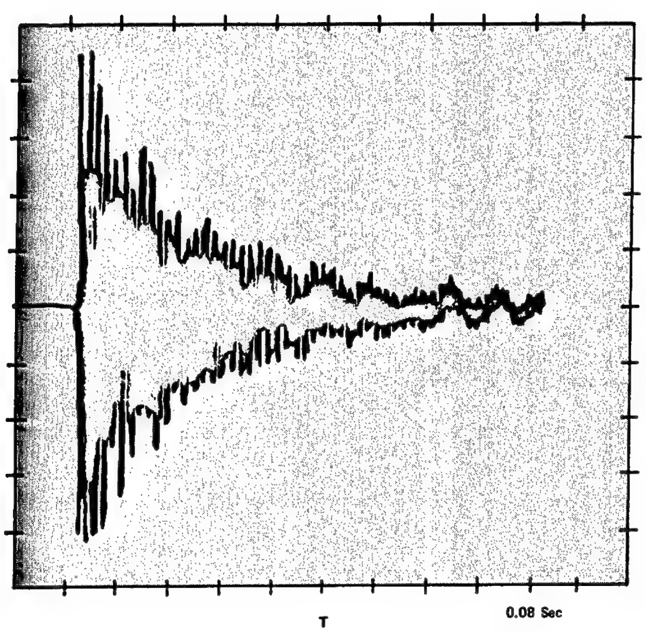


Figure 9

The frequency work was initially performed in the 0-20,000 Hz range. However, after experimentation, the range was narrowed to 0-5000 Hz. Several vessels were tested in this range; all vessels had a dominate frequency in the 19-2000 Hz range and 26-2800 Hz range. Each vessel's dominate frequency was reproducible with in 12 Hz (the accuracy of the analyzer).

The vessels were struck at various locations along the cylindrical section and in each instance the same frequencies remained dominate. When the dome was struck, only changes in magnitude of dominate frequencies occurred. This was true up to the very end of the nozzle where the 1900 and 2600 Hz frequencies were no longer distinguishable.

Delaminations Detectable

To determine if a delamination was detectable by reading the dominate frequency, a unit was selected that had 2,000 Hz dominate frequency. This unit was placed in a vise and stressed until the first audible sound occurred. Visual inspection of the unit showed no signs of damage. The unit was retested and a 25 Hz shift in the dominate frequency was observed (2,000 to 1,975 Hz). The shift was also reproducible. The unit again was placed in a vise and stressed until a visual delamination occurred. Upon retest, the dominate frequency again shifted from 1975 to 1825 Hz. In addition, upon viewing of the real time signal, a damping effect was also noted. This initial work indicated not only that the test was capable of detecting a delamination, but possibly the extent of a delamination.

The results of the initial work appeared sufficiently encouraging to continue exploration. This included the acoustical testing of 35 units before and after hydrotest. Both of the dominate frequencies were read for both conditions. An attempt was made to evaluate the real time damping effect; however, the effect was not nearly as dramatic as the unit crushed in the vise.

Another problem in assessing the damping effect was the amplitude of the recorded wave. It was difficult to achieve the same db amplitude. This is not necessary to determine decay rate; however, it allows a direct comparison. The exact decay rate can be determined but it is a tedious and time consuming procedure with the equipment used for the testing. Therefore, the investigation of decay rate was dropped. The investigation of frequency changes continued.

Testing Poses Questions

One vessel was selected at random to better understand the frequency change and determine at what point delamination can be detected. The first pressurization cycle was at 2000 psi. A larger than expected change in frequency occurred at 1912.5 to 1875 Hz. The pressure for each test was increased 2000 psi and frequency readings were taken after each test up to 12,000 psi. The

largest changes occurred at 6000 to 8000 psi range (1862.5 Hz reading). However, at the higher pressures (10,000 and 12,000 psi), the frequency readings increased and returned to 1875 Hz. The exact reason for this behavior is unknown; however, it was theorized the higher pressures consolidated the case wall, yielding an upward shift in frequency level. The entire quantity of data is presented in Table 4.

The final test to determine the applicability of the acoustic vibration technique was to select units which had either large or small frequency shifts between pre- and posthydrotest. Eight units were selected and burst. The burst values of the units were within the normal population but did not correlate with frequency shifts. The data is presented in Table 5.

Table 4

	1900Hz Range	Frequency Change From Pre-Hydro	2600Hz Range	Frequency Change From Pre-Hydro
Pre-Hydro Test	1912.5	—	2712.5	—
	1912.5	—	2712.5	—
2000 psi	1875.0	37.5	2662.5	50
	1875.0	37.5	2662.5	50
4000 psi	1875.0	37.5	2650.0	62.5
	1875.0	37.5	2650.0	62.5
6500 psi	1862.5	50	2637.5	75
	1862.5	50	2637.5	75
8000 psi	1862.5	50	2637.5	75
	1862.5	50	2637.5	75
10,000 psi	1875.0	37.5	2662.5	50
	1875.0	37.5	2650.0	62
12,000 psi	1875.0	37.5	2650.0	62
	1875.0	37.5	2650.0	62

Table 5

S/N	Frequency Change (Hz) @ 1900	@ 2600	Burst Pressure (psi)
76	0	0	12,408
77	0	+12	13,113
78	−37.5	−50	13,327
80	−37	−37.5	12,035
54	−12.5	−50	14,420
82	−12.5	−12.5	14,389
89	−37.5	−67.0	11,934
96	0	0	14,460

It was expected units S/N 76, 77, and 96 would have had higher burst values than 78, 80, 54, 82, and 89. However, as can be seen in Table 5, this did not occur.

Dominant Frequency Sought

Attempts were made to analytically identify the dominate frequency seen in the experimentation. The analytical determination was complicated by shape and the fact that the case is anisotropic. The initial analytical method used to determine the frequency of the case structure was one developed by V. S. Gonthevich which is based on the Rayleigh-Ritz method using beam function and the Donnell-Mustari Shell Theory. This solution is for an isotropic free-free cylindrical shell to simulate the case.

The basic ID and wall thicknesses were used while the modulus and length were varied. This yielded frequencies as low as 2874 Hz for a 6 inch long cylinder with a modulus of 2.0×10^6 psi to a high 9868 Hz for an 11 inch long cylinder with a modulus of 5.1×10^6. All frequencies were higher than the experimentation readings of 2000 Hz and 2600 Hz. It appeared at this time a more sophisticated analysis was required. A normal mode analysis was selected.

NASTRAN TESTING

The normal modes analysis was performed using the NASTRAN Finite Element program.

NASTRAN is a general purpose computer program designed to analyze the behavior of elastic structures under a range of loading conditions using a finite element displacement method approach. The normal modes analysis, part of NASTRAN's dynamic analysis capability, solves for frequencies and shapes of the natural modes of complex structures. It yields normalized, modal, grid point displacements.

The motorcase was modeled using the structural elements of NASTRAN. The case wall was modeled using a combined plate bending membrane element (CQUADZ). This element is formulated by adding the stiffnesses for bending behavior and membrane behavior. The forward adapter ring was modeled using a beam bending element (CBAR). The beam element is a lineal element whose properties and behavior variables are continuously distributed along a line segment that joins two grid points.

Symmetry Permits Equal Elements

As a result of the symmetry of the motorcase, the case was modeled in the circumferential direction by dividing the circumference into sixteen symmetrical grid points

(22.5 degrees each). The motorcase was also divided along the axial direction; however, the axial locations of the grid points were determined in order to accurately model the motorcase contour. The entire motorcase was modeled using 224 plate elements. The forward adapter ring was modeled using 16 offset beam elements. These elements were offset to model the eccentrical stiffening effect provided by the adapter ring. To simulate the boundary conditions consistent with the acoustic emission tests, the motorcase was modeled using free-free boundary conditions. Constraints were placed on the case taking advantage of the symmetry of the problem.

The normal modes for the motorcase can be determined within any frequency range. Since the results of the acoustic tests indicate a fundamental frequency at 1900 to 2100 Hz, the NASTRAN analysis was performed to determine the normal modes in the frequency range between 1700 Hz and 2100 Hz. The program identified only one frequency in the search range at 2040.8 Hz.

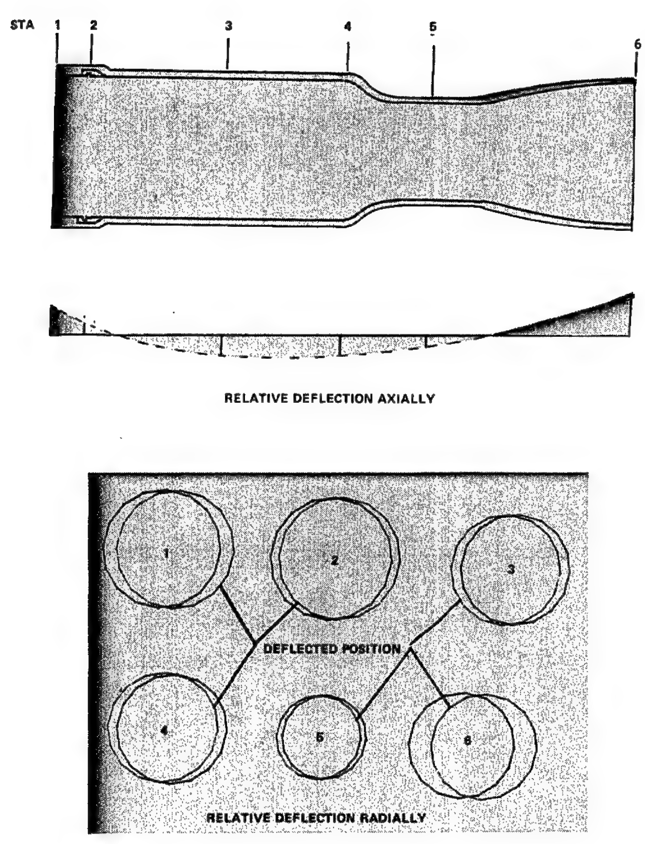
The output of the NASTRAN normal modes analysis consists of a tabulation of the natural frequencies (eigenvalues) and their associated mode shapes (eigen functions). The mode shape for each material frequency was then displayed graphically at selected cross sections along the axial direction. Typical results are presented in Table 6. The deflected shapes are shown in Figure 10.

The results of the analysis show the case vibrates in a beam mode (axially along the case) and appears to be basically a full wave. There was no circumferential dilation at 2040.8 Hz. This frequency and mode shape should be equivalent to the dominate frequency seen in the acoustic impact testing.

Table 6

Grid Pt	Radial* Displacement	Circumferential* Displacement
193	-6.044×10^{-1}	0.0
194	-5.584×10^{-1}	2.288×10^{-1}
195	-4.273×10^{-1}	4.228×10^{-1}
196	-2.313×10^{-1}	5.525×10^{-1}
197	0.0	5.980×10^{-1}
198	2.313×10^{-1}	5.525×10^{-1}
199	4.273×10^{-1}	4.228×10^{-1}
200	5.584×10^{-1}	2.288×10^{-1}
201	6.044×10^{-1}	0.0
202	5.584×10^{-1}	-2.288×10^{-1}
203	4.273×10^{-1}	-4.228×10^{-1}
204	2.313×10^{-1}	-5.525×10^{-1}
205	0.0	-5.980×10^{-1}
206	-2.313×10^{-1}	-5.525×10^{-1}
207	-4.273×10^{-1}	-4.228×10^{-1}
208	-5.584×10^{-1}	-2.288×10^{-1}

*Displacements are normalized.



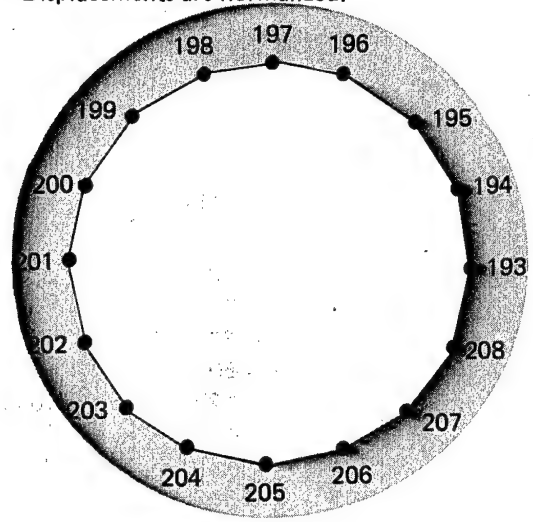


Figure 10

Cavity Frequencies Independent

The frequencies of the case cavity were also evaluated. The cavity frequencies were 617 and 3631 for the axial and radial modes. The frequencies were above and below the dominate frequencies observed in the experiment; however, a 525 Hz frequency was seen at a low amplitude in the experimentation. This frequency did not change due to hydrotest and appears to be a cavity frequency.

At this point it still was felt the acoustic testing should yield some results. The entire problem was reconsidered and a new theory developed. The new theory was: **strength levels could be determined based on the pressure level that causes a shift in dominate frequency.** To test the theory, 10 units were pressurized in 500 psi steps to 7000 psi. The dominate frequency was determined after each pressurization. After the 7000 psi pressure cycle, a prediction of burst pressure rank was made and the units were burst. The data is shown in Table 7.

The data has been presented in two populations: head and tail stock units. This is because of the different burst levels. The prediction was correct only three times out of ten. The method predicted the burst order of S/N 69, 71, and 70. This is considered inclusive. The equipment used to determine the frequencies was only able to discern a 12.5 Hz change. The majority of the units only change 12.5 Hz. The maximum change was 25 Hz.

Table 7

Head Stock Units	Pressures that Dominate Frequency Change, psi	Burst Pressure, psi
69	500	11,968
71	1000	12,713
73	1500	14,317
75	2500	13,595
77	4500	13,036
$\bar{X}$		12,998
σ		701
C_v		5%
Tail Stock Units	**Dominate Frequency Change, psi**	**Burst Pressure, psi**
72	1000	15,115
76	2500	14,971
74	4500	13,679
78	4500	14,806
70	5500	15,231
$\bar{X}$		14,600
σ		707
C_v		5%

PRODUCT EVALUATION

To evaluate the cases fabricated in the third year of the program, the dimensional and structural reproducibility were studied. The major finding from the study was that there were two distinct populations from the unit fabricated. This was true both structurally and dimensionally. The findings came as a surprise and have been related to the winding pattern.

The goal of the program was, after hydrotest, to demonstrate an inside diameter tolerance control of ±0.001 in. and 0.002 in TIR. The head stock population had a dimension spread of 2.2895 to 2.2950 in. or 0.0055 in. which is greater than the desired 0.002 in. Eighty seven percent of the units were out of drawing tolerance. The tail stock group spread was 2.2900 to 2.2930 in. or 0.0030 in. However, only seven percent were out of drawing tolerance. If the tolerance spread would have been ±0.0015 in., all tail stock units would have been in tolerance. Interestingly enough, the mandrels were basically identical—within 0.0005 in. for all mandrels. This led to the conclusion that the winding pattern affected the dimensional stability of the units.

Hydrotesting Induces Deviations

The TIR readings were less satisfactory. The head stock range was as high as 0.0075 in. with 71% being out of tolerance. The tail stock range was, again, better with a maximum reading of 0.0055 in. with 34 percent being out of tolerance. If the TIR tolerance would have been 0.0035 in., eight percent would have been out. In general, the dimensional control on the units wound at high speeds were poorer than those wound during the second year's program. It was known the winding patterns were slightly different at the high speed. However, when reviewing both year's data, it appears the case is unable to consistently meet the ±0.001 in. and 0.002 TIR requirements after hydroproof. A tolerance range of ±0.0015 and 0.003 TIR would reject few units provided. If a tolerance change is not acceptable, there is a method of improving the dimensional control. This would be to incorporate some hoop wraps in the design. It should be noted that before hydrotest all inside diameters were within tolerance and only four units were out of TIR requirements. The out of tolerance condition occurred due to the hydrotest. This would, however, change the design. An addition of some hoop wraps and reduction of helical would not substantially change the design or any estimates made in the program.

There was also a variation in weight from the head to tail stock—358.5 vs. 382.8 g. This was, again, due to winding pattern. As in the second year's program, the units in the lower position of the machine averaged 19.8 grams higher than the top windings. The average difference during the second year was 17.5 grams and was attributed to excess resin on the lower winding. This was corrected in the third year's program; however, a difference still exists. Since the resin problem had been solved, the extra weight is from some other cause. Again, the winding pattern is the cause. The delivery heads were mounted on a vertically cantilevered member, with the lower head being farther away from the mounting. With the high speed winding and the dynamics of the vantilever, there was a slight difference between the upper and lower windings. The only area of performance where this difference showed up was in a weight increase of about 2.9 percent.

Table 8

Operation	Manhour Requirement
Winding	8
Storage	2
Machining and Mandrel Removal	4
Mandrel Cleaning	3.5
Mandrel Assembly	4
Mold Release	4
Liner Application	4
Hydrotest and QC	10
Materials Handling	8
Fill-In Man	8
	55.5 Manhours

Structural Reproducibility Checked

To evaluate the structural reproducibility, 25 units were burst. The results were used to make reliability and reproducibility estimates. The first observation was the structural capability was different between the head and tail stock units. The tail stock group burst higher. Therefore, both structural and dimensional performance of tail stock units were better. Although no units failed below minimum burst pressures of 11,400 psi, statistically failure would occur in 2.7 percent units from the head stock and 4.8 percent from the tail stock. This averages to 3.75 percent. The probability of bursting below a maximum operating pressure of 7,000 psi is two in one million for the tail stock and six in one hundred thousand for the head stock.

Eleven additional units were burst in the posttest mechanical evaluation portion of the program. These were not included in the reliability numbers because of a different pressurization cycle; however, it does not appear the results would be changed significantly.

The evaluation of the units showed the winding pattern is very critical. Small changes are seen in weight, dimensional stability, and strength. These differences can be eliminated with a machine specifically designed for this job; one which has adequate controls and dynamic response.

PRODUCTION COSTS ESTIMATED

The estimated production costs remained true to the original forecast. The change was only about two manhours of labor for 500 units. Four hours of labor were removed from the winding process; however, two hours were added for dimensional inspection. Shown in Table 8 are the raw manhours required to fabricate 500 units.

It appears the production cost of the case, as designed, should run in the $11 to $15 range for 1978 dollars. The cost breakdown is shown in Table 9. The costs will be a function of the facility, accounting system, overheads, profit margins, production quantity, etc. The table shows typical costs with typical factors included in each individual item. The special tooling costs were amortized over one million units.

Table 9

Labor	$ 2.77
Supervision	0.72
Production	0.40
Roving	1.92
Resin	0.21
Adapter	2.07
Closure	2.67
Snap Ring	0.64
Liner	0.04
Packing Crates	0.13
Tool Bits	0.08
Shipping	0.07
Special Tooling	0.48
	$12.20

Editor's Note: The U. S. Army Missile Command wishes to acknowledge the outstanding engineering work performed on the filament wound rocket motorcase by Hercules Engineer John Sollinger, who conducted the technical work directed by MICOM leading to the successful culmination of the project.

Ed Gardner—MTO Veteran

The Manufacturing Technology Office at DARCOM in Alexandria, Va., will never be quite the same after the recent retirement of Ed Gardner, veteran of many years of ManTech efforts. While in the MTO, he became known as the supreme authority on ManTech matters related to Commercial Commodities Acquisition. This included everything from undershirts, towels, bedpans, gasoline, trucks, tractors, tires, velocimeters, steam cleaners, and watercraft to the regulations covering same; also "their proponents, defenders, attackers, and other assorted cigar smoking radicals," to quote one of Ed's associates. Fast talking defender of the MT/MACI faith, Gardner was considered invincible by his adversaries, because he had so numerous staunch friends.

Ed was no stranger to meeting a challenge. He entered the military service in 1942 as an Aviation Cadet and remained in aviation until he left the service as a 1st Lieutenant in 1947. He worked for many years at Lockheed's Sunnyvale, California, Missiles Division before joining the Missile Command in 1964, when he returned to Government service. He gained experience in the PM Weaponization at the AMC, later working with AMSAA in the Command, where his major efforts were with the 2.75 rocket and adaptation of the TOW missile to helicopter use. Prior to joining the DARCOM ManTech office in 1976, Ed spent several years in the Engineering Division of the RD&E Directorate at the Missile Command after the AMSAA office was closed.

Gardner will be missed by more than those associated from his engineering days. While at DARCOM, he was instrumental in leading the effort to have the Snack Bar on the 6th floor to be run by the blind. All his friends, associates—and adversaries—will miss him, as will the DARCOM ManTech effort. Happy landings, Ed, from all of us!

Editor's Note: The Army ManTech Journal staff wishes to express its appreciation to the Missile Command for its outstanding effort in providing materials for an extended series of articles. Particularly helpful in gathering material for these articles—only a few of which appear in this issue—was Mr. Bobby Austin, Project Engineer in the Manufacturing Technology Directorate at MICOM. Readers who wish to acquire more detailed information than is contained in these articles should contact Mr. Austin at (205)876-8445 or write to him at the U. S. Army Missile Command, DRSMI-ETT, Bldg. 5400, Redstone Arsenal, Huntsville, Alabama 35809. Along with Mr. Austin's other duties, he serves as the contact point for manufacturing technology inquiries for the command, and in the course of these duties is responsible for documenting the technology transfer of MICOM manufacturing technology projects.

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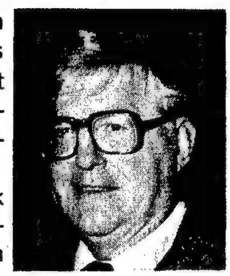
ABOUT THE COVER:

Melt extraction and melt drag techniques are seen being used in this photo, as aluminum flake and fiber products are formed directly from a molten bath, eliminating property variations inherent in production of these items by machining. The Series 100 modifiers produced by Transmet Corporation, Columbus, Ohio, are designed for high electrical and thermal conductivity in most resin systems. Processing ease is assured by the soft, nonabrasive particle character.

Photo by Battelle staff photographer Bill Weider.

Comments by the Editor

An unusually wide spectrum of subject matter is featured in this issue of the U. S. Army ManTech Journal, which contains articles on electronics, fuzes, computerized planning, propellant processing, hot isostatic pressing, powder metallurgy, directional solidification, and the establishment of American military manufacturing technology in a foreign country.



DR. JOHN J. BURKE

The article on the metal nitride oxide semiconductor block oriented random access memory (MNOS BORAM) device developed by Westinghouse and Norden highlights an Army mantech project that has drawn considerable attention as a technical accomplishment that will save vast sums of money, meanwhile creating a whole new level of reliability and efficiency of operational performance. ERADCOM should be proud of its role in the development of this breakthrough of electronics technology through the support of high technology industrial firms. One of the most remarkable facets of the MNOS BORAM project is the development of a class of the devices specifically for military use in a configuration that fits into an overall plan for orderly growth of the technology. Changes

The article on fuze power supplies is the forerunner of numerous articles on new mantech accomplishments by the Harry Diamond Laboratories through the support of the Munitions Production Base Modernization Agency at Picatinny Arsenal. Many new ideas are being developed by HDL, and the Army ManTech Journal plans to report to its readers the highlights of these efforts.

The U. S. Army Missile Command scores another significant advance with its computerized process planning described in the article on Page 28. Process planning is the key activity which determines how a product is to be manufactured, and in fact is the first step in manufacturing. MICOM has advanced the state of the art dramatically with this project and significant savings are expected as the technique is applied to Army manufacturing processes. The extreme complexity of machined parts is expected to be handled effectively by this new system, which allows continual cost/design interrelationships to be considered and appropriate changes made during the production phase.

A unique situation is described in the article on manufacturing the M-16 rifle in Korea—a situation that may become more common in the years ahead as military equipments are fabricated by joint efforts of multiple nations. This is already becoming

a regular occurrence in the contracting of European firms for components for aircraft—part of the production of which will be purchased by the nation in which the subcontractor operates. The Colt company in establishing a production facility in Korea to

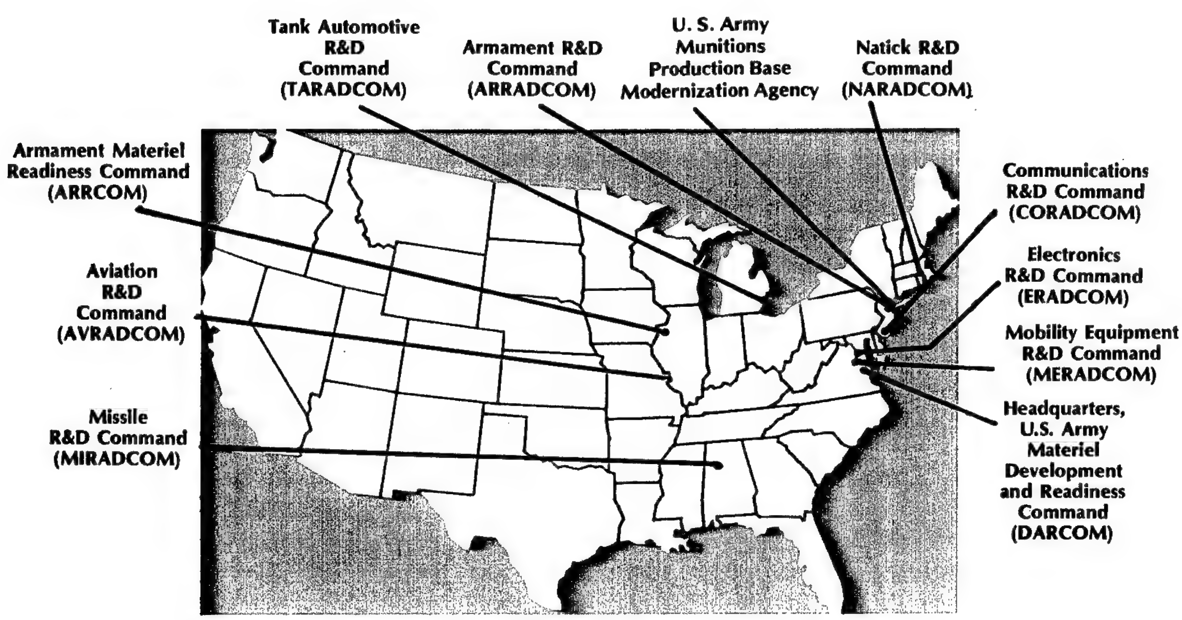
Hot isostatic pressing is rapidly being expanded in use, as depicted in the two articles on Page 37 and Page 41. In the case of the G.E. use of HIP, turbine disks and cooling plates for turbine engines are fabricated, whereas the TRW use centers around parts for the Army's M-85 .50 caliber machine gun. In both uses, dramatic savings of materials are combined with the production of high quality forged parts.

In the article on the MICOM project carried out by Atlantic Research Corporation, the dramatic benefits encountered from the injection molding process represent man-hour savings of better than fifty percent compared with the volumetric fill techniques previously practiced. Regardless of whether the savings are in labor—as in this case—or materials—as in the case of HIP—real benefits are being realized from the prudent expenditure of mantech funds by our military agencies.

Casting of single crystal turbine blades by directional solidification again has advanced through the work of Jetshapes and TRW under the sponsorship of the U. S. Air Force for Detroit Diesel Allison Division of General Motors. A breakthrough is described in this effort which produced a shell molding system that does not react with the nickel and cobalt base alloys used during the process, which involves high temperatures for long periods of time.

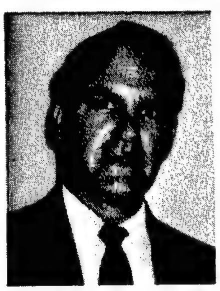
The staff of the U. S. Army ManTech Journal is pleased to announce the forthcoming publication of a special issue featuring the Manufacturing Technology Advisory Group Annual Meeting October 19-23 in Miami Beach. This issue will present some interesting insights into the DoD, Army, Air Force, and Navy activities in the mantech area and will introduce for the first time an article reflecting the Department of Commerce role in our MTAG effort. We believe the readers will find this fifth issue, which will be distributed complimentarily to attendees at the meeting and also to our regular subscribers, will provide some highly interesting and comprehensive coverage of this critical phase of the national MT effort.

DARCOM Commands Actively Implementing New Manufacturing Technology Methods



New Storage Medium Saves $22 Million

Smaller, Lighter, More Reliable



JOE E. BREWER is an Advisory Engineer with the Westinghouse Electric Corporation in Baltimore, Maryland. In his fourteen years with Westinghouse he has been engaged in the design, development, and manufacture of subsystems and components based on advanced integrated circuit technology. For the past eight years he has specialized in memory technology, with emphasis on the development of nonvolatile semiconductor memory. Previous to joining Westinghouse he was employed for eight years at the Centralab Division of Globe Union Inc. His last position at Centralab was Manager of Advanced Design, where he was responsible for new product development, with emphasis on hybrid integrated circuits. Mr. Brewer is a senior member of the IEEE. He holds four patents and has published or presented twenty technical papers. He received a B.S.E.E. degree in 1961 from the Milwaukee School of Engineering and has done graduate work in Mathematics at the University of Wisconsin.

HERBERT L. METTE is Leader, Advanced Integrated Circuit Techniques Team at the U. S. Army Electronics Technology and Devices Laboratory. He also is Deputy Army Member on Working Group B of the DOD Advisory Group on electron devices. From 1965 to 1972 he was Chief, Integrated Devices Techniques Branch after serving as research physicist at the Laboratory from 1956. He received his M.S. degree in Physics from the University of Goettingen, West Germany in 1953, after which he worked for the German National Bureau of Standards for a period of three years. A naturalized U. S. citizen, he is a Fellow of the American Physical Society and a senior member of the IEEE. A holder of three patents, he has published forty-four technical articles or presentations. He was project officer for the Army on the MNOS BORAM project.

Editor's Note: A major contributor to the MNOS BORAM project has been Mr. William Bond of Norden Systems, who will be a principal author of the second part of this article which is scheduled to appear in the next issue of the U. S. Army ManTech Journal.

Newly developed multichip hybrid circuits planned for use in the Army's Black Hawk Helicopter have set new levels of efficiency, reliability, and physical size for "Accident Information Retrieval Systems" (AIRS). The manufacturer of AIRS, Hamilton Standard, estimates that MNOS BORAMs (metal nitride oxide semiconductor block oriented random access memory) will be three times as reliable, ¼ the size, and ⅓ the weight of miliarized magnetic tape, a storage medium that might have been used.

Westinghouse Defense and Space Center in Baltimore developed the 6002 MNOS BORAM chip, which will be used in the "Accident Information Retrieval System" (AIRS) for the Black Hawk Helicopter with Hamilton Standard as prime contractor. Use of the devices holds promise of savings up to $20,000 per helicopter x 1107 to be equipped, or a total savings of $22 million with full scale production.

The MM&T project to establish a pilot production line for these metal nitride oxide semiconductor block oriented random access memory multichip hybrid circuits has recently received high level attention due to its outstand-

ing success. This project provides a significant example, also, of capital investment by a contractor reflecting Army manufacturing technology effort.

The MNOS BORAM MM&T project has proven to be a significant factor in the growth of this technology and its military application. The devices show promise of filling urgent needs for wide temperature range high density nonvolatile solid state storage.

Producibility The Question

During the early 70's the potential of MNOS BORAM was well recognized within the Army. Technical feasibility had been proven, but questions concerning producibility still existed. It remained for a manufacturing methods and technology project to face the practical issues of achieving an economically viable production capability. The purpose of this MM&T project was to establish that production capability. At the conclusion of the effort, the Government was to have a source of supply for MNOS BORAM hybrid circuits—a pilot production line with a demonstrated throughput capacity of 1875 hybrids per month on a five day week, one shift basis.

$4 Million Private Capital Invested

The MM&T effort encompassed all of the activities necessary to develop, specify, operate, and debug the required production capability. In the immature phases, two sets of engineering samples were produced as a learning vehicle and as a means by which progress could be measured. After acceptable tests and test programs were established, a group of confirmatory samples were produced to prove that the product was ready for production. Extensive testing and documentation was required with the confirmatory samples. Finally, a pilot production run was performed. During the pilot run, yield and throughput information was gathered to demonstrate that the required capacity of 1875 hybrids per month had been achieved.

During the course of the MM&T project, the Westinghouse Electric Corporation acted independently to supply capital equipment and process development that enhanced the MNOS BORAM production capability. Westinghouse investment in MNOS BORAM is now approaching four million dollars.

The combined MM&T and Westinghouse efforts have produced significant progress in BORAM chip fabrication, electrical tests and screens, and in hybrid circuit fabrication.

Three Major Applications In Use

Military needs for storage of digital data in several application areas can be met cost effectively by using MNOS BORAM devices packaged in hybrid circuits. This MM&T project was the last step in the development of this technology before the engineering development of specific memory systems.

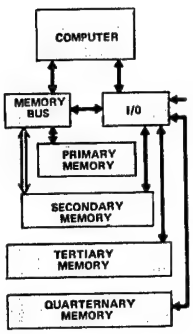
The cost, reliability, power dissipation, environmental limitations, and physical bulk of digital data storage constitute a major consideration in the implementation of a modern electronic system. This is particularly true in military applications that may involve high stress environments or may place emphasis on achievement of some specific attribute such as small size or low power. In at least three classes of applications, MNOS BORAM shows promise of providing significant advantages over available alternative technologies—secondary storage, airborne recorders, and program storage.

The traditional approach to implementation of **secondary storage** is to employ a magnetic drum or disc. For many military applications this is simply not a viable alternative, because drums and discs cannot stand up in the required environments. In fact, it was the lack of suitable secondary storage alternatives that led to definition of the BORAM concept.

The idea of a Block Oriented Random Access Memory and the acronym BORAM was originated by Mr. David Hadden in June of 1963 at what was then ECOM. A BORAM was defined as an all electronic memory with certain performance goals. No implementation technology was specified.

Concept New In Military Systems

In most computer systems, memory is organized in a hierarchical fashion in order to achieve required capacity and performance at a tolerable cost. Figure 1 illustrates the general concept. Primary memory is randomly word addressable. It provides fast data access and is relatively expensive. Secondary and higher order memory may be addressable in a different fashion. Higher levels have progressively larger capacity, slower access, and lower cost. Hierarchy design involves tradeoffs at each level of



Structural Nomenclature	Functional Nomenclature	Present Technologies	Emerging Technologies
Primary	Main Store	Core	N–MOS
Secondary	Backing Store	Bulk Core, Drum, Disc	MNOS, CCD BEAMOS
Tertiary	Bulk Store	Disc, Tape	MNOS, MBD
Quarternary	Archive	Tape	Video Disc, Optical

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Figure 1

such parameters as access time, storage capacity, and cost. The design is usually conceived to achieve some desired global objective like maximum computer throughput per dollar.

Hierarchical concepts have worked quite well in commercial computing applications, but have had little impact on many military systems. For example, it is quite common for military real time programs to be stored in main memory because the access delays associated with electromechanical storage cannot be tolerated. In some cases, the use of drums or discs is prevented by environmental considerations such as temperature or mechanical stress.

The technical feasibility of using MNOS to build a BORAM unit suitable for military use was demonstrated by the design, fabrication, and evaluation of a computer secondary storage unit. This advanced development was carried out by the Westinghouse Electric Corporation. The work was sponsored jointly by the U. S. Army Electronics Command and the Naval Air Systems Command. Module evaluations were conducted at the Naval Air Test Center and at Fort Monmouth. A final technical report is available.

Model Exceeds Military Specs

Figure 2 shows the 16.8 megabit advanced development model that was delivered in October of 1975 with a 1/64th population. This early design confirmed that an all electronic, self contained, general purpose secondary storage unit could be built. No external controllers or power supplies were required for operation. The design avoided problems common to electromechanical storage originating from moving parts, vacuum systems, moisture, and dust particles. The unit's data access delay of less than 30 microseconds was more than 100 times better than the fastest drum. No rotation latency time existed. The flow rates were designed to match the maximums allowed by the computer interface specifications. The highly modular design demonstrated volume and weight advantages over comparable fixed head magnetic systems.

Government evaluators confirmed the performance and physical characteristics of the advanced development model by direct measurement. The unit was interfaced to several host computer systems and was observed to perform well. By actual demonstration, it was shown to be compatible with standard military hardware and software.

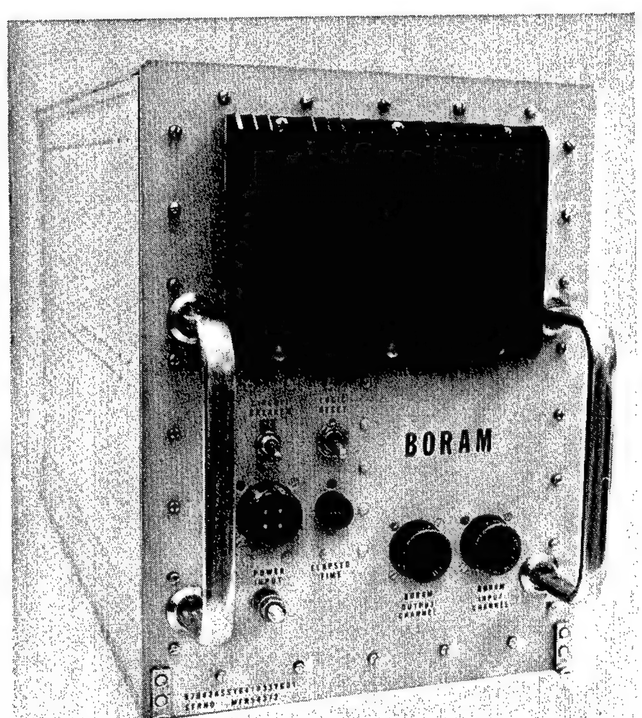


Figure 2

The flexibility of the design allowed easy interfacing and promoted built in diagnostic capabilities.

Studies conducted on MNOS BORAM designs patterned after the advanced development model have tended to be positive. The Naval Air Development Center investigated the life cycle cost of MNOS BORAM, in which reliability potential was shown by models to support MTBF's on the order of 10,000 hours. Initial procurement costs were projected to be competitive with discs and drums using an 8,192 bit MNOS chip. The cost was projected to become more favorable as the bit density per chip increased. Modularity and repairability were shown to be definite assets.

Overall, the evidence indicates that MNOS BORAM can be a superior alternative to fixed head electromechanical storage. However, it should be noted that secondary storage is only one of many potential application areas.

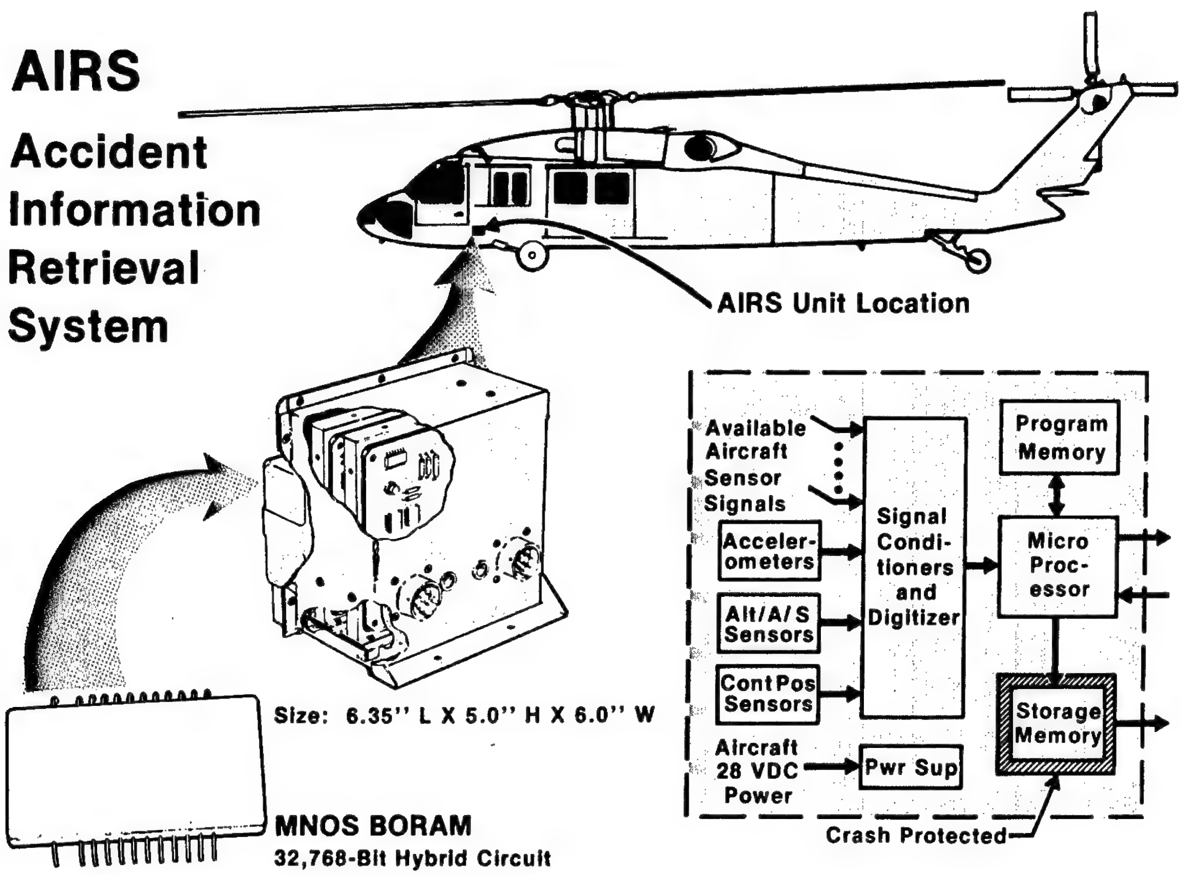


Figure 3

Airborne Recorders Survive Better

The Accident Information Retrieval System (AIRS) being developed by Hamilton Standard for AVRADCOM is an example of a class of application which can benefit from the unique characteristics of MNOS BORAM. Figure 3 shows the elements of AIRS. Sensors monitor important variables on the aircraft, and this data is constantly examined by a microprocessor system. A history of the flight is maintained in a solid state nonvolatile memory formed by one MNOS BORAM hybrid circuit.

The memory is a critical element of the AIRS. The mission of the system if to provide a record that will allow investigation into the cause of an accident. The data must survive in the environment of a crash, and the memory must be capable of providing reliable operation in the most hostile flight environments.

To ensure survivability, Hamilton Standard has developed a "crash protected" module to enclose the BORAM hybrid circuit. The module provides mechanical and thermal protection.

Recently, the efficiency of the protected memory was demonstrated by the successful completion of qualification tests per Federal Aviation Regulation Part 37.150, Aircraft Flight Recorders TSO-C51a. At the beginning of the test series a data pattern was written into the BORAM hybrid circuit. At the end of the stress tests the hybrid circuit was read, and the data pattern was checked. All bits were found to have been correctly retained.

The initial stress was a 1000g, 5 millisecond, ½ sine shock test in six directions. A penetration test was performed that involved dropping a sharp pointed (0.05 in.^{2}) member attached to a 500 pound weight from a height of ten feet onto each side of the protected module. The module was also subjected to crush forces of 5,000 pounds for five minutes in each of the three main orthogonal axes. A flame test exposed the module to temperatures of 1100 C for a half hour over more than 50 percent of the module surface. Finally, the module was submerged in salt water for 36 hours.

The fire associated with a crash is probably the most demanding aspect of the requirements placed on the memory. Water is enclosed in the protected module aroung the BORAM hybrid to limit the temperature rise. Test results at Hamilton Standard show that the hybrid should not be exposed to more than 160 C. Tests by Hamilton Standard on MNOS BORAM devices have confirmed data retention after exposure to 160 C for two hours.

The wide temperature range of the MNOS BORAM chips is a definite asset in the AIRS. The operating temperature range is -55 to +125 C. This feature, plus nonvolatility and high density packaging make MNOS BORAM the best available technology for this type of airborne recorder.

Program Storage

The storage of computer programs is a requirement common to almost all military electronic systems, and a variety of memory technologies have been used for this purpose. For many systems, MNOS BORAM hybrid circuits can provide a very attractive means of program storage. They are particularly suitable where electrical reprogrammability is a desirable feature. They also offer wide temperature range operation, high packaging density, low power dissipation, and high performance in a paging mode.

Westinghouse is currently developing a program storage card for use in the APG-66 radar system. This particular design uses 16 BORAM hybrids that contain 16 of the 8,192 bit BORAM chips. A single 6.4 x 8.3 inch card pair stores 131,072 words, where each word contains 16 bits.

The 8 kbit BORAM chip, dubbed 6008, is pin for pin compatible with the 6002 and is manufactured by identical processes. A current ERADCOM contract, DAAK20-80-0259 (MM&T: 8 kbit MNOS BORAM), is seeking to verify the producibility in quantities of this device. The 6008 also is being supplied by Westinghouse for the MIFASS (Marine Integrated Fire and Air Support System).

Best Technology for Hybrid Circuits

MNOS BORAM devices packaged in hybrid circuits offer the military user several important features. While the significance of these items can only be weighed in the context of a specific application, it is well to at least tabulate them for general consideration.

The choice of MNOS BORAM technology over present day memory alternatives usually keys on one or more of the following features:

- Silicon IC fabrication technology
- Full -55 to +125 C operation

- Nonvolatile data storage
- Data access in terms of microseconds
- Bit density growth potential
- Normal IC voltage interfaces
- Low power operation.

The cumulative investment in silicon integrated circuit technology is of enormous magnitude. Manufacture of MNOS BORAM uses these proven materials, processes, and equipment. As the art improves because of VHSIC and VLSI advances, MNOS BORAM will improve.

Because of the push of IC technology to finer geometrics, it is certain that MNOS BORAM will achieve higher bit densities per chip. Advanced circuit design studies indicate that 256K to 1M bit chips will emerge.

Of the available nonvolatile memory technologies, MNOS BORAM is most often compared with magnetic bubbles. Bubble data access times are many milliseconds, versus tens of microseconds for MNOS. Bubble output signals are millivolts, compared with volts for MNOS. The -55 to +125 C operating temperature range (with data retention nonoperating up to 160 C) for MNOS BORAM cannot be approached by even the most optimistic projections for bubble devices.

High Density Packaging Economically

MNOS BORAM is conducive to very simple high density packaging. A BORAM hybrid need contain only the memory chips. The permanent magnets and field coils associated with bubble devices are not required.

Obviously, MNOS BORAM chips can be placed in a wide variety of single or multiple chip packages. Westinghouse has used dual inline packages, flat packages, leadless carriers, and multichip hybrid packages (MHP). For the broadest range of military applications, the hybrid package offers the best density and lowest cost.

Hybrid circuit density advantages are obvious to most observers, but the economics of the hybrid approach may not be. The cost of one hybrid containing 16 chips should be compared with the cost of 16 discrete packages. For military use, a significant portion of the device cost is associated with testing and screening. The cost to test and screen one hybrid (including yield loss) is only slightly more than the cost to test and screen one discrete package. This cost on a per chip basis strongly favors the hybrid approach.

MNOS BORAM CHIP FABRICATION

The MNOS BORAM 6002 chip was the primary development vehicle for the MM&T project. It currently is fabricated using P-channel metal gate technology. The nitride oxide dual dielectric insulator enhances reliability and makes possible the realization of nonmemory and memory transistors within a single integrated circuit.

Transistor Structure Better Protected

An MNOS nonmemory transistor performs the same type of functions as a conventional MOS transistor. The physical form of the MNOS device is similar to the MOS device, except that the insulator region is composed of two dielectric layers.

Two types of memory transistors have been used in previous MNOS work at Westinghouse. Figure 4 compares the unprotected and protected transistor structures. The major physical difference is that the thin tunneling oxide does not overlap the P+ diffusions in the drain source protected (DSP) device.

Unprotected transistors exhibit severe degradation with use. This class of transistor is also difficult to employ in integrated circuit arrays because of depletion mode operation while in the high conduction state.

The DSP transistor has been shown to provide reliable memory operation beyond 10'' erasewrite cycles. The central device design concept was to protect the thin oxide from stresses associated with material imperfections and/or electric fields. The thick nonmemory oxide employed close to the source and drain determines the gate breakdown potential. Junction fields do not affect the stability of the tunneling oxide.

The DSP device can be thought of as a memory transistor in series with two nonmemory transistors as shown in the equivalent circuit of Figure 4 (B). The P-channel enhancement mode nonmemory transistors determine the high conductance state of the DSP structure, therefore the DSP device is confined to enhancement mode operation. In large integrated arrays this is an important feature. Interconnection schemes for erase, write, read, and standby can be achieved without contending with difficult parasitic current problems.

Some of the advantages of the DSP transistors can be summarized as follows:

- Reliable memory operation for 10'' high field erase write cycles can be achieved.

- Enhancement mode operation allows the parallel connection of transistors in large arrays in a manner compatible with read circuitry.
- Drain and source breakdown voltages are increased to that of conventional nonmemory transistors.
- DSP transistor gate capacitance is reduced to about 25 percent of unprotected transistor gate capacitance. This allows four times as many DSP devices to be driven in parallel in an array with equivalent response times.
- DSP transistor gate to source capacitance is much smaller than that of unprotected transistors. Address voltage feedthrough to memory detection circuitry is reduced.

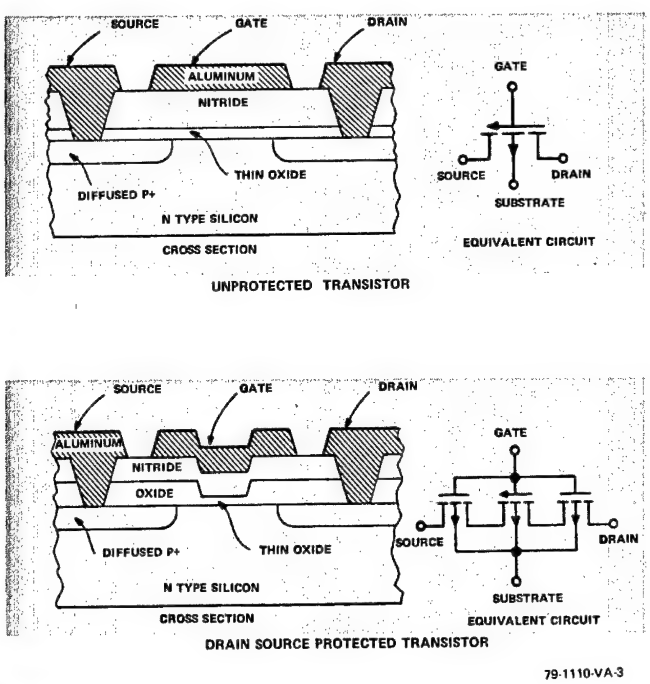


Figure 4

BORAM IC's From Years of Work

At Westinghouse, BORAM integrated circuit development has been concurrent with memory system development. As a result, the best characteristics of the MNOS technology have been deliberately applied to achieve computer secondary storage requirements.

To achieve cost effective performance, a solid state computer secondary storage unit must provide fast write and read capability. RAM organized MNOS electrically alterable memory chips are incompatible with this application because millisecond write times are required. To overcome this limitation, MNOS BORAM chips are designed for 10 to 100 microsecond write times and operate in parallel on blocks of data to provide adequate data rates.

A BORAM chip contains a fully decoded random access memory and a shift register for data I/O (See Figure 5). A single read or write involves the transfer of many bits in parallel into the shift register. The contents of the shift register may be shifted at megahertz rates. This arrangement allows the MNOS RAM to operate at modest speeds compatible with high yield production, while the shift register maintains the high bit transfer rate required.

Experience with volatile semiconductor RAM production has shown that yield to dynamic response criteria such as access time is a major impact item. MNOS BORAM devices should suffer very little production loss to dynamic criteria. The chip circuitry when operating in a secondary storage unit will never be required to operate near the performance limits of the device.

MNOS BORAM chip development has been a process of continuous simplification and refinement over several years. Initial designs required two level metallization and single transistor cells to achieve productible die sizes. Attempts to manufacture these devices led to identification of critical circuit and process problems. Successive designs eliminated and/or avoided these difficulties (see Table 1).

The most successful design prior to this project was the BORAM 6000C. It employs a single level metal interconnect and a two transistor cell. The two transistor cell has proven to be a major factor in high yield production in the presence of variability of transistor characteristics. It has also improved the opportunities for thorough test of the memory array, and provides longer effective data retention times than single transistor cells.

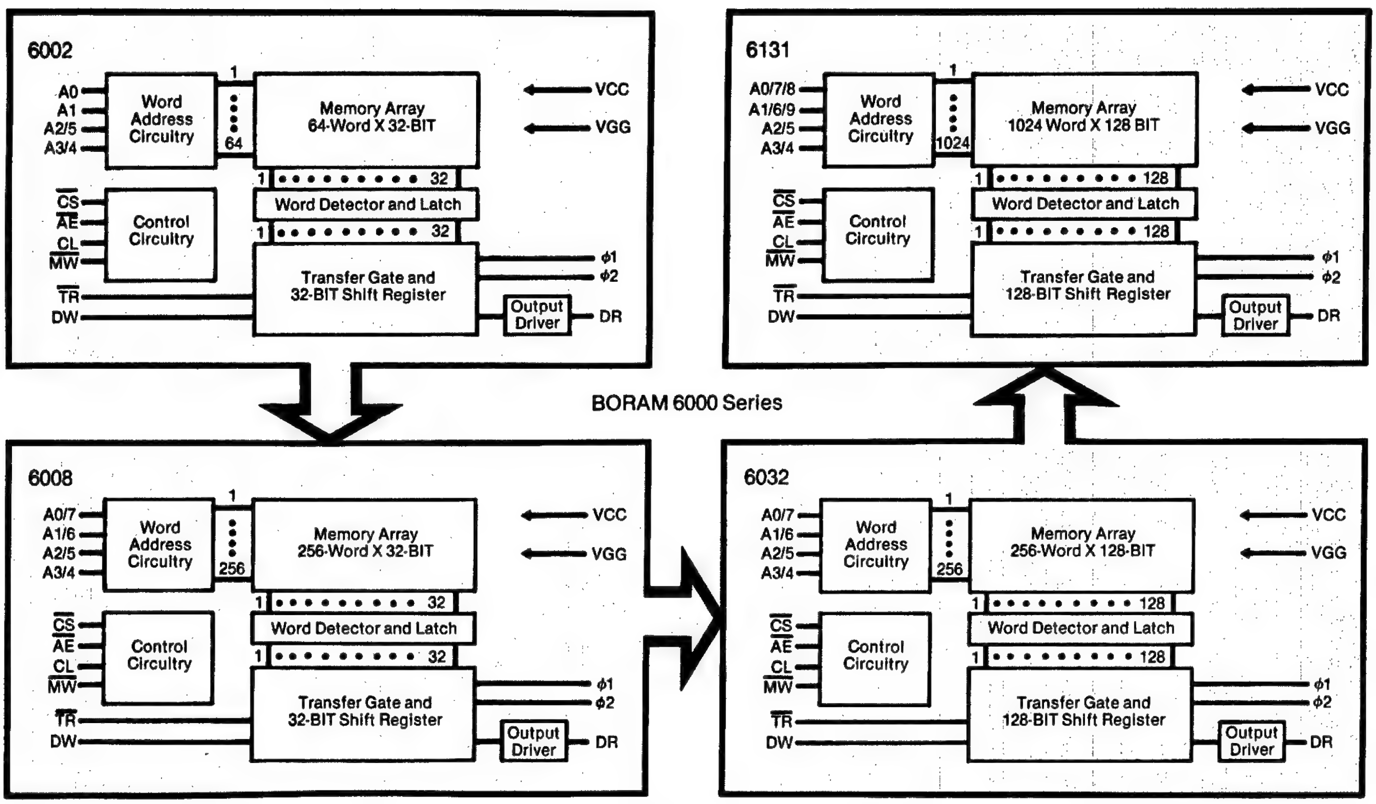


Figure 5

CHIP DESIGN MANUFACTURING FEATURES

The cost effectiveness of MNOS BORAM will be affected by many factors which come into play at different levels of product use and manufacture. In particular, the long term growth and application of the product should be considered. Of immediate concern is the need for the design to be compatible with the natural variability of current materials and processes.

Bit Density to Grow

Because of strong development trends in the semiconductor industry and because of detailed circuit design projections, it is anticipated that the number of bits per BORAM chip will increase sharply in the near future. Westinghouse is concerned that the investment in production capability and in circuit and system development not be made obsolete by this thrust to higher bit density.

To accomplish this purpose, Westinghouse established a plan for controlled growth of bit capacity per chip. As shown in Figure 5, a series of chips called the 6002, 6008, 6032, and 6131 were planned. Therefore, the bits per chip grows from 2K to 8K to 32K, and then to 131K.

All of the chips in the series are pin for pin compatible. A larger device can be used in place of any smaller device. This controlled growth scheme allows conversion of memory systems based on the smaller chips to the larger

DEVICE NUMBER	FIELD THRESHOLD SUPPRESSION APPROACH	DIE SIZE, mils	MASKING OPERATIONS	METAL LAYERS	TRANSISTORS PER CELL
6000	Nitride field shield	154 x 175	11	2	1
6000A	Nitride field shield	154 x 170	12	2	1
6000A	Ion implant	154 x 170	12	2	1
6000B	Channel stoppers	151 x 169	8	1	1
6000C	Channel stoppers	163 x 169	8	1	2
6002	Ion implant	99 x 128	9	1	2

Table 1

chips with minimum cost impact. Each chip is an evolutionary improvement over the preceding device and necessarily incorporates new features which enhance utility and yield. For example, the 6008 device has lower dissipation and more relaxed waveform timing requirements than the 6002 chip.

The overall effect of these changes is illustrated in Figure 6. Increased numbers of die sites implies reduced cost per die. The cost of processing a Si wafer is relatively fixed, thus with an increased number of die sites, the cost per wafer is reduced.

Die Size Reduced

A first principle of silicon integrated circuit design is to make the die as small as possible consistent with available process limitations. Small die area improves yield and increases the number of dice per wafer. An early objective of the MM&T was to simplify and shrink the BORAM chip. The point of reference at the beginning of the effort was the 6000C chip that measured 163 x 169 mils. The reduced die, the 6002 chip, measured 99 x 128 mils. This is 46 percent of the 6000C area.

Area compression was achieved in the memory array portion of the chip by using two row address decoders. The decoder pitch on either side of the array was approximately the same as that for earlier designs, but because the left and right row selection circuits were interleaved, the cell density was almost doubled.

Surface Contour Simplified

An important consideration in integrated circuit manufacture is to make sure that the interconnect metal maintains adequate thickness over the surface contours of the die. If the chip design contains abrupt steps of dimensions which approach the thickness of the metal, significant yield and reliability problems can be expected.

The design of the 6000C incorporated an approach which held the largest step to a reasonable magnitude and caused that step to be "beveled" or sloped. It was desired that the same advantage for the 6002 chip be maintained.

The largest step in insulator thickness occurs where the metal enters or leaves a field region. The 6000C controlled field parasitics by using channel stoppers. The 6002 employs an ion implant to raise the field inversion threshold.

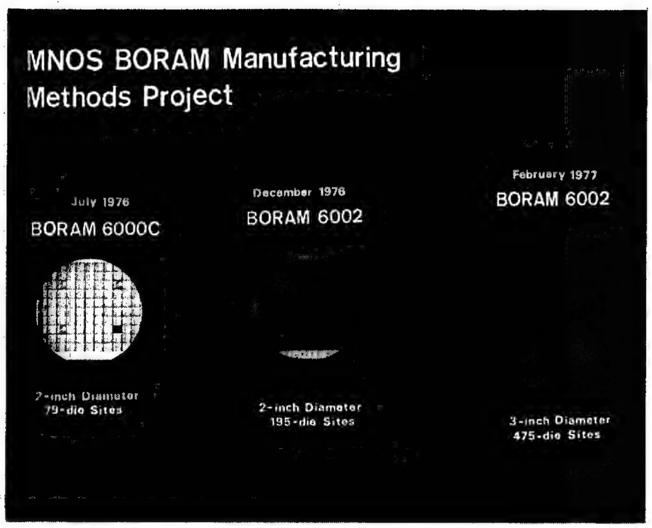


Figure 6

This approach requires less chip area and maintains the same simplified surface characteristics.

The field silox consists of 7000 angstroms of undoped oxide and 3000 angstroms of doped oxide. During the gate and contact etch, the high etch rate of the doped oxide causes a sloping of the oxide steps. Cleaning before metal deposition then removes all of the doped oxide.

Tape Carrier Compatibility Retained

During the MM&T project and for near term production, gold ultrasonic wire bonding will be used. In 1980 and 1981 the process will be converted to tape chip carrier. One design consideration for the 6002 was to maintain compatibility with tape carrier technology.

To make sure that the future conversion would not encounter unusual problems, Westinghouse initiated tape carrier development in conjunction with the MM&T activities. Figure 7 shows a closeup of a 6002 device with tape carrier leads. Figure 8 shows a hybrid circuit populated with tape bonded 6002 chips.

Westinghouse has fabricated and tested tape bonded BORAM hybrids using several different types of tape and processes. These experimental devices are being used as development vehicles to prove the processes and tooling and to confirm the reliability of the end product.

CHIP PROCESSING

The Westinghouse MNOS BORAM chip processing sequence involving nine masks was established at the beginning of the MM&T project. During the course of the effort, significant improvements were made in nitride deposition and in photoimaging.

Photoprocessing Busiest Step

Two objectives were kept in mind during the development of the MNOS BORAM wafer processing sequence. The first was simplicity—reduce the sequence to the minimum number of maskings and avoid yield impacting topological features. The second objective was to use only well known and characterized individual process steps. By doing this, the risks in manufacturing would be minimal.

Figure 9 provides a simple concept of how material flows during MNOS BORAM fabrication. The characteristic cyclic nature of semiconductor manufacture is evident. A wafer is first prepared by some photo and/or chemical process step, and then it is given some treatment which modifies the surface structure of the wafer.

The modification operations are oxide growth, diffusions, and depositions. These stations see the wafer only one time during fabrication. The photolithographic, etching, and cleaning processes see the wafer many times. Photoprocessing experiences the highest work load vol-

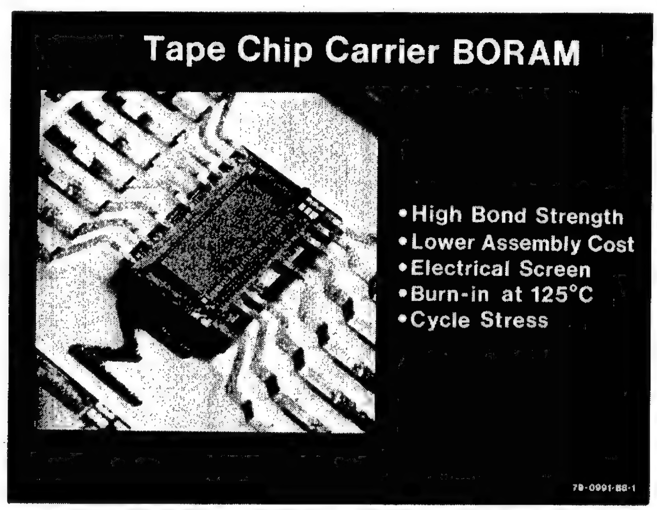


Figure 7

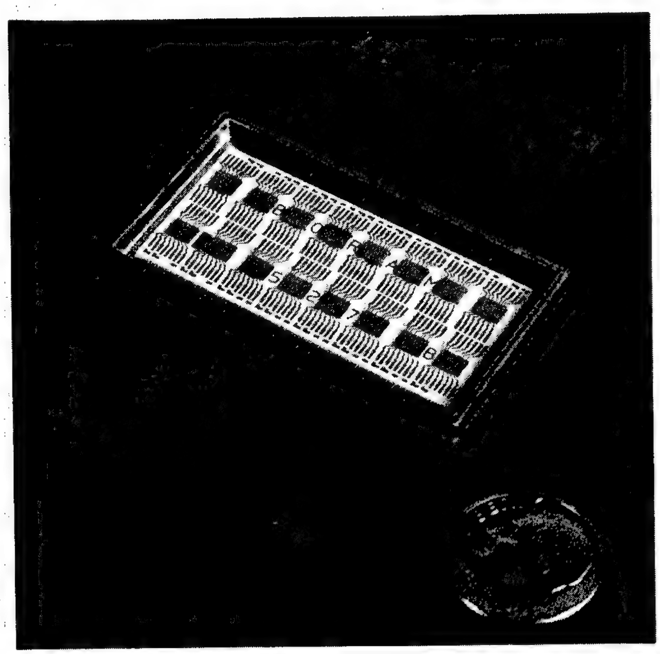


Figure 8

ume. Figure 10 illustrates how the wafer cross section is modified after various steps.

Pressure Deposition Marks Progress

At the beginning of the MM&T project a matter of some concern was control of the nitride. In particular, it was known that electric field stresses on the tunnel layer were very sensitive to the nitride thickness. Thin nitride could lead to excessive stress and rapid degradation of retention characteristics.

Nitride thickness control was improved considerably by a change from atmospheric to low pressure chemical vapor deposition (LPCVD). The introduction of LPCVD was a major contribution toward achievement of reliable low cost production. It should be noted that this advance came about because MNOS represents silicon integrated circuit technology, and it will make use of the improvements made in that technology.

Photoimaging Steps Slashed

One advancement in BORAM manufacture came about too late to be included in the MM&T activity, but it is of such significance that it deserves mention. This is the use of a direct step wafer (DSW) aligner. In order to understand the significance of the DSW, it should be compared with the processes used during the MM&T. Figure 11 provides a summary of the two approaches.

The MM&T made use of an automated plate production system. Chip design and layout was accomplished using a CALMA design system that features multiterminal input stations, powerful software, and large storage capability. A computer controlled pattern generator and photorepeater provided positional accuracies and line width tolerances to one quarter of a micrometer. Working photomasks are derived from a series of contact printing operations that originate from one master print and a set of submaster prints. Photoimaging on the wafer is accomplished by aligning a working photomask with a given wafer, bringing the mask into contact with the wafer and then exposing the photoresist.

In the DSW approach, an X10 reticle is used to optically project the image of a single die directly onto the wafer. The wafer is mounted on a movable stage, and the wafer is automatically repositioned to allow exposure of each die site. The DSW approach eliminates the manufacture and control of one to one photomasks.

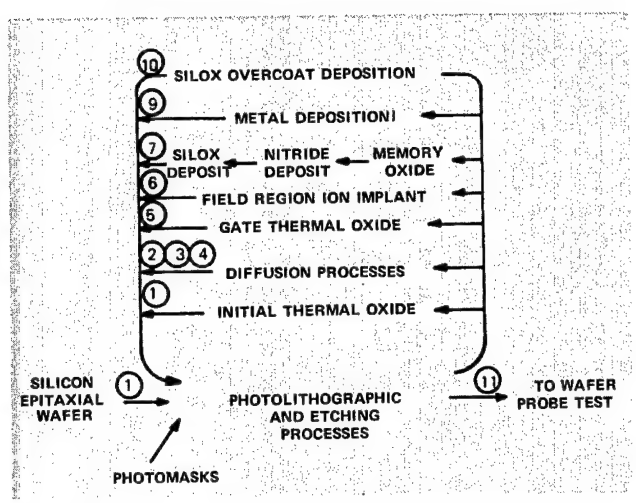


Figure 9

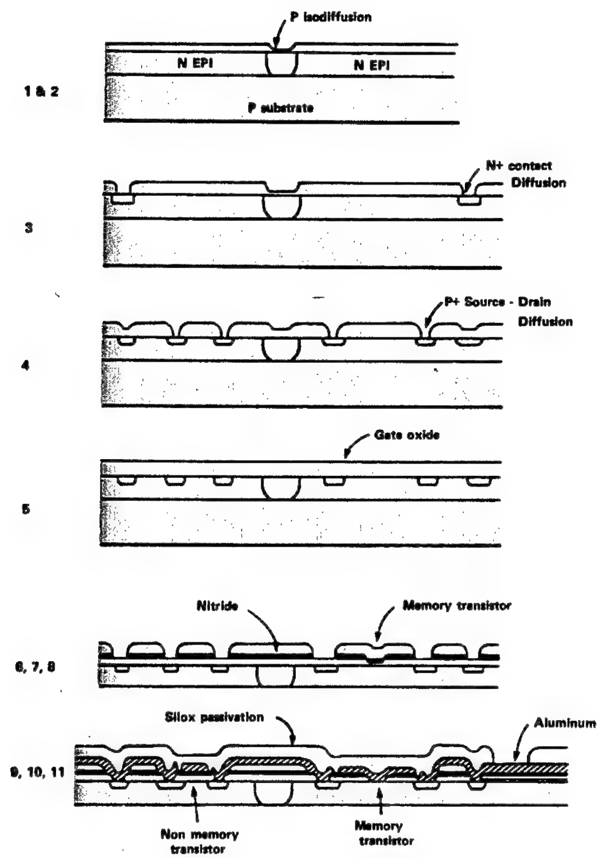


Figure 10

Multiple Advantages Inherent

The DSW approach provides several advantages over previous methods.

(1) It is noncontact printing. Because the mask and

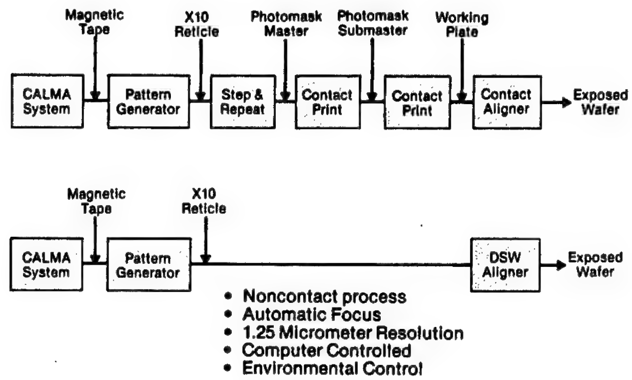


Figure 11

wafer do not touch, no damage is introduced to either the mask or the photoresist coating.

(2) The DSW mask is much less critical for small imperfections. The DSW reticle is X10, and a defect would have to be on the order of 10 micrometers in size in order to be resolved on the wafer.

(3) The DSW provides better than a factor of two improvement in registration and alignment over one to one projection systems. The unit is capable of ± 0.35 micrometer (three sigma) registration with ± 0.1 micrometer alignment error.

The DSW features laser metering of the stage placement, light integration for constant exposure energy, computer control of the system, and automatic focus maintained by photoelectric detection of the surface within each image area. The DSW is capable of routinely producing 1.5 to 1.75 micrometer lines in positive resist.

Experience with the DSW has resulted in sharply increased yields on BORAM 8K bit chips. Because of the ability to process finer lines and spaces, it has opened the door to immediate reductions in die size. Also, progress toward high bit capacities per chip has been accelerated.

Editor's Note: This article is considered by the Editorial Staff to contain information of such unusual impact to the field of electronics manufacture that, rather than reduce its length and lose much of its content, it will be carried in two sections. Part II will appear in the next issue of the ManTech Journal and will cover sections on the electrical testing and screening of the MNOS BORAM chip and its fabrication into hybrid circuits.

Ensured Reliability, Interchangeability

M16 Rifle—"World" Weapon?

STUART C. PLETTNER is Manager of Military Manufacturing at the Firearms Division of Colt Industries. He joined Colt eight years ago as the Korean Project Director, where he managed the total program to install an M-16 plant in Pusan, South Korea, for the Koreans to produce rifles for their own armed services. Prior to joining Colt, Mr. Plettner held a variety of manufacturing management positions with Bell & Howell, Textron, Federal Products Corp., and Lightolier. He is a graduate Mechanical Engineer from the University of Cincinnati in 1942.

Would you expect two samples of a complex, precision item produced by different companies nearly halfway around the world from each other to meet the same high quality standards and to have completely interchangeable parts? Colt Industries not only believed this, but has proved such a performance level can be achieved.

In an effort to select standardized rifle and machine gun ammunition for use by all NATO forces, tests are being conducted at Rock Island (Illinois) Arsenal under the sponsorship of the U. S. Army Armament Materiel Readiness Command to qualify one or more standard rifles. This is part of an international program called RSI (rationalization, standardization, and interoperability) that has strong DoD backing. The M16, manufactured by Colt's Firearms Division, is being evaluated along with rifles from five other nations. To their advantage, Colt already has established procedures for manufacturing standardized weapons with interchangeable parts in different parts of the world.

Used in 26 Countries Already

The M16 is now the standard infantry weapon in the United States and 25 other countries outside NATO. In addition to its domestic production by Colt Firearms Division, the M16 is built by Colt licensees in Singapore, Korea, and the Philippines. Through extensive MM&T efforts, Colt has refined manufacturing methods and standardized quality assurance operations at all plants. Despite these widely separated manufacturing facilities, the differing cultures and customs involved, and a wide range of output requirements, quality standards and interchangeability are being preserved down to the part level.

Figure 1 illustrates the M16 assembly, which includes 130 basic parts. The 12 most critical and difficult to produce parts are fabricated in the Colt plant. The other 118 parts are supplied by subcontractors. Getting reliable, interchangeable parts could be a logistical nightmare, but Colt has developed methods to overcome any problems through their extensive R&D and MM&T efforts. At the same time, they have emphasized light weight—a must for the infantryman who lives with the weapon—without sacrificing firepower or quality. A look at a few of the processes involved provides insight into the scope of this effort and illustrates how Colt has maintained reliability and interchangeability in weapons manufactured in different countries.

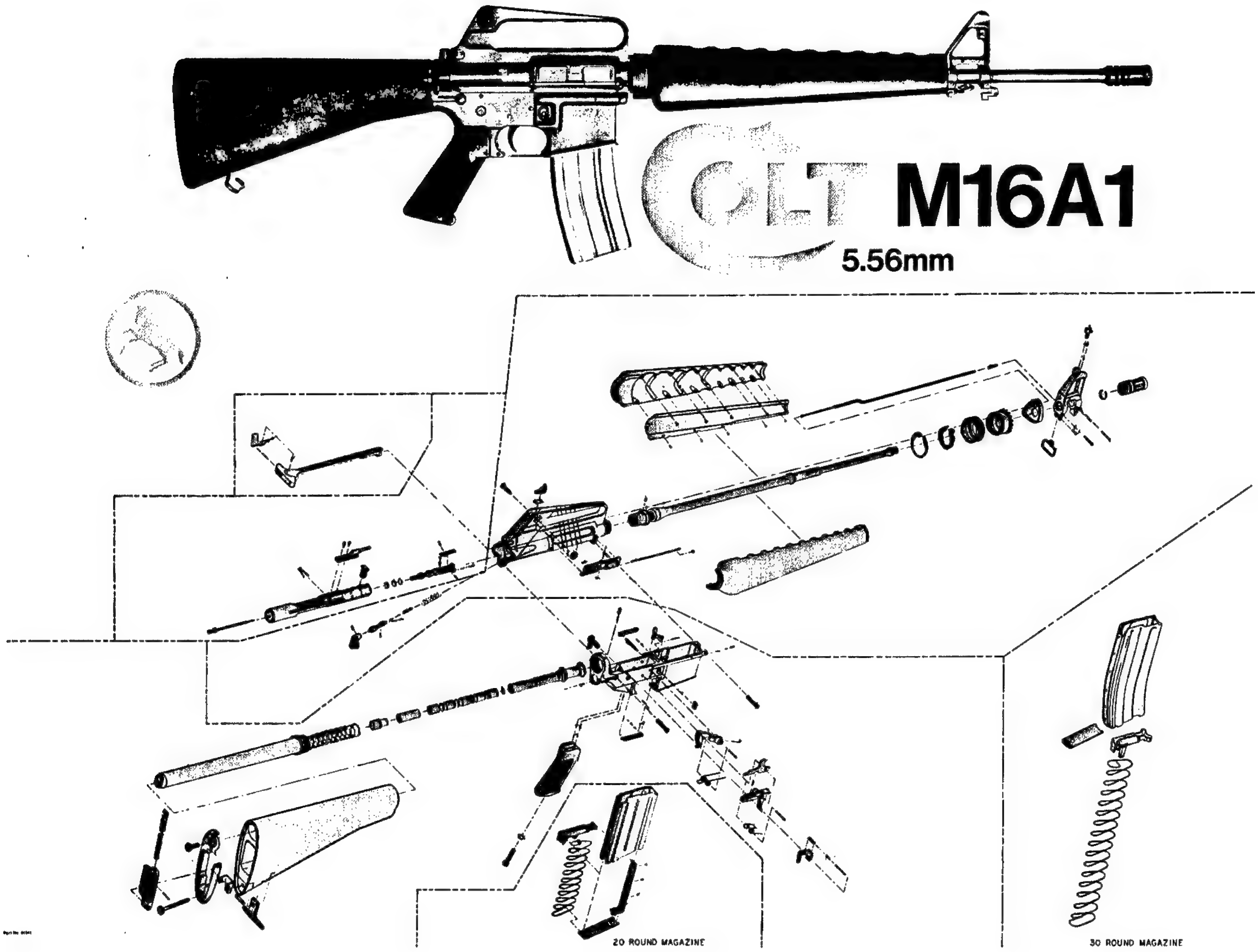


Figure 1

Cold Forming For Barrel

The barrel is the most complex part on the rifle and requires the most operations; those that produce the rifled bore are most critical. During the early stages of M16 production, Colt experimented with several alternative processes to make the bore, seeking both an improved product and reduced labor costs. Present methods resulted from a good deal of patience, ingenuity, and perseverance.

In initial production, the bore was rifled by a cutting process similar to shaping. Grooves were cut to depth one at a time and the barrel was then indexed to the next groove. This was a slow process and did not give a particularly smooth finish. The effort then turned to cold forming, which allowed production of all grooves and lands simultaneously. This produced a good finish with a harder surface due to the cold working effect. Cold forging also was investigated but was not as successful in producing the sharp corners that are required on the rifling. In addition, cold forging costs were considerably higher. Consequently, Colt has standardized its process around the following cold forming method.

Rods of hot rolled barrel steel are cut to length (20 inches) and stress relieved prior to machining. Colt uses a high quality Crucible steel that is tough but that can be machined by their unique broaching process.

"Button" Broach A Marvel

Next, the barrels are drilled through their length to produce a 0.2135 inch diameter bore. Drilling is followed by a reaming operation and a pull broaching procedure that sizes the barrel bore to a tolerance of 0.0002 inch and removes all radial marks in the bore. A "button" broach is then pushed through the bore to cold form the grooves and lands, which will twist the bullet one turn per twelve inches of travel.

The broach is made of #1 carbide. Figure 2 shows its builtin lead angle and the pilot and final forming diameters. The tool is pushed by a rod, but due to the lead angle, turns itself as it forms the metal of the bore. Its unique design allows it to form extremely accurate grooves. The need for accuracy is especially critical near the muzzle end, where the projectile is guided on its ultimate path. To insure continued accuracy in rifling, the broaches are discarded when they wear to the lower process limit.

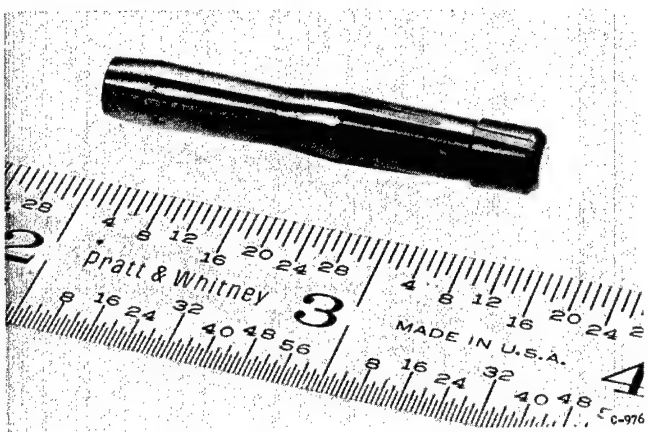


Figure 2

Plating Helps Control Tolerances

Initially, bore finishing operations presented problems in dimensional control, which again were critical to weapon performance. Following final forming of the rifle, the barrel is given a second stress relief heat treatment, which causes the bore to contract slightly. The outside diameter then is turned on a lathe in a two pass operation, first removing sizeable amounts of material, which slightly enlarges the bore. The tolerance problems these operations introduce have been overcome through another MM&T effort. Any dimensional variations are compensated for when the bore and chamber are chrome plated; the plating operation is controllable, so slight differences from process dimensions can be corrected by adjusting plating thickness to produce a bore to specifications.

Lightweight, Low Cost Magazine

The M16 was designed to be fed by a 30 round quick change magazine, with each soldier carrying five to ten loaded magazines in reserve. Thus,low cost and light weight, as well as reliability, were design requirements for the magazine. Consequently, Colt has developed manufacturing methods that ensure strength and reliability while providing lightweight parts that will not overload the foot soldier.

Dry Lube Baked In

The magazine box is made from two aluminum stampings spot welded together, as shown in Figure 3. A bottom plate is held in position between these stampings by a

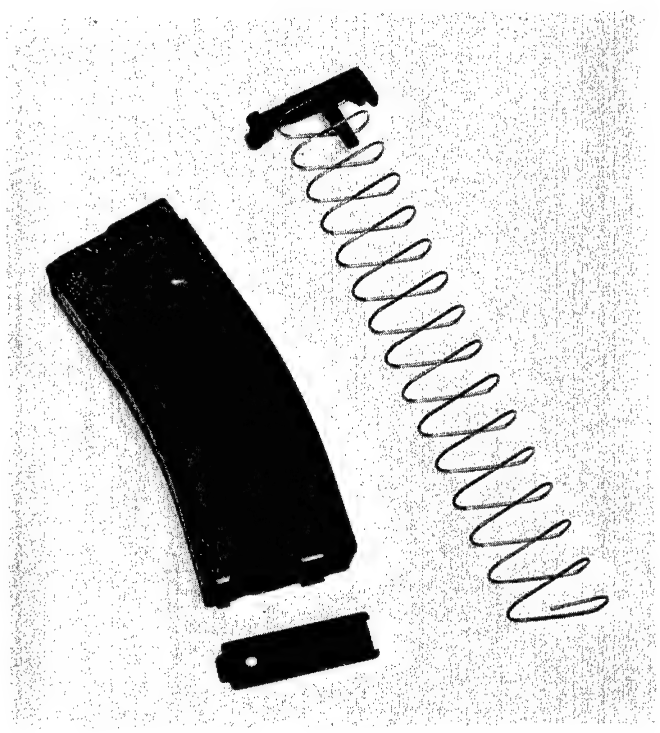


Figure 3

special "square" coiled spring. The spring also pushes the plastic follower against the cartridges to feed them into the chamber. The upper portions of the stamped housing are rolled inward to form lips which position the cartridges for feeding. A precipitation hardening heat treatment on the finished case prior to hard coat anodizing provides the required lip strength. To make sure that the cartridges and the follower move freely, a dry lubricant is applied to the magazine box by a dipping process followed by baking at 250 F for one hour. This lubricant also increases the corrosion resistance of the anodic coating.

Receiver Production Automated

The upper receiver (Figure 4), made from a 7075 aluminum forging, is a critical part requiring a great deal of close tolerance machining. As a result of intensive MM&T efforts, the machining is now largely automated—really a necessity to hold tolerances and to minimize costs. Dial indexing machines perform 43 operations at significant savings in labor cost. Although somewhat specialized, these machines are considerably less expensive and more flexible than a transfer machine and can accommodate the range of locations necessary to meet tolerance requirements. Group technology techniques have been applied carefully to equipment arrangements for these machining operations to minimize transfer delays.

In the production process, qualifying milling cuts are made on the bottom and the two ends of the forging. This prepares it for the first of seven dial indexed machines—a special four position machine that performs gun drill, gun ream, and turn, face, chamfer, and recess operations. These operations provide a large diameter hole and front face configuration that serve as locators in most of the succeeding operations.

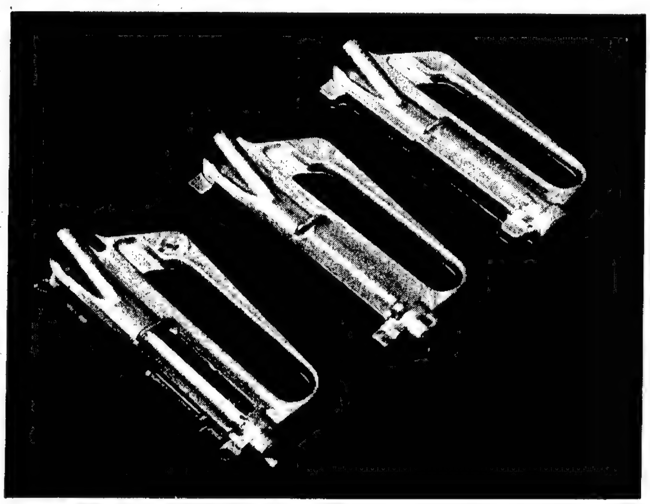


Figure 4

In Process Gages Total 189

The other six index machines include three profile milling machines, two special drilling machines, and a special machine for milling, drilling, and tapping. There are then eight remaining machining operations—three light milling cuts, a slotting operation, an internal spline broach, a hone to finish size the large bore, a polishing operation to remove the remaining forging flash, and a vibratory finishing to remove burrs and chamfer sharp edges. After dimensional inspection, the machined receiver is sandblasted to provide a clean matte surface for a hard anodize coating that is dyed black. The large finished bore is sprayed with the same dry film lubricant used on the magazine and baked for one hour at 275 F.

Checks For 115 Characteristics

Extensive quality assurance measures are applied to all steps in receiver production—189 gages are used in process to check the progress at various stages. These quality assurance checks are taken at specified frequencies varying from one in five to one in fifty pieces. As a final inspection, 115 characteristics are checked on a sample basis using 64 gages. Universally applied quality assurance procedures such as these have made it possible for Colt to interchange any parts from one plant (domestic or foreign) with those from another and to maintain high reliability regardless of where a weapon is produced.

Plastic Adopted For Buttstock

The M16 design departed from the conventional by using a plastic rather than wooden buttstock. Lightness again was a consideration, but considerable care was required to ensure adequate strength in the plastic part. To provide cost effective production, while maintaining a quality part, expensive R&D and subsequent MM&T efforts were undertaken.

In making the buttstock shown in Figure 5, a glass filled phenolic is molded by a transfer process, starting with a 6.4 ounce cold compacted preform. Two parts are molded simultaneously in a 200 ton press. After deflashing the parts and drilling one hole in each, the internal cavity of the molded buttstock is filled with a polymeric isocyanate urethane, which forms a rigid foam that sets in about

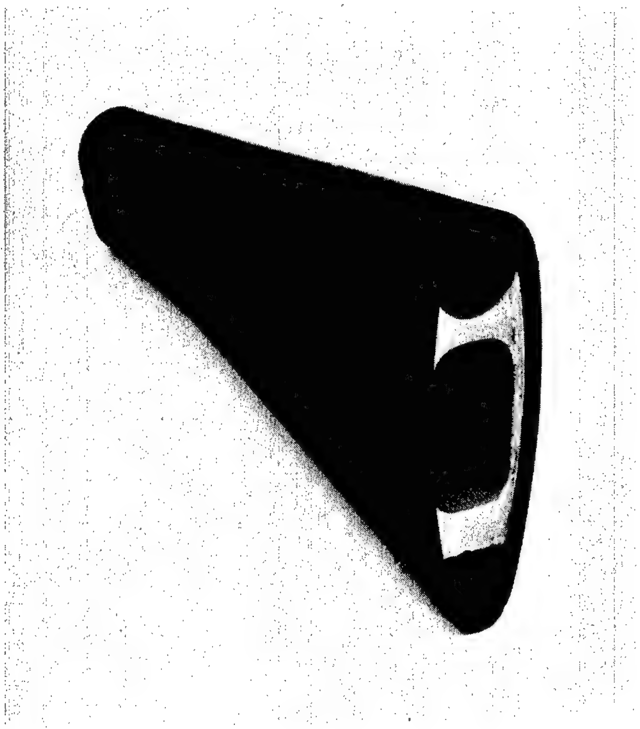


Figure 5

ten minutes. Using a male die, the cavities for the receiver extension and the stowage compartment are formed. The resulting part has properties comparable to those of the more common wooden stock. In addition, the desired dull black color is molded in, so that no finishing operations are required.

Investment Casting For Hammer

The hammer shown in Figure 6 is one of five investment castings used on the M16. Although several precision machining operations are required to complete the part, the use of investment casting significantly reduces the number of such operations. Following casting, the flash and gate are removed and the pivot bosses are straddle milled. Required holes are made on a ten spindle machine that drills, reams, countersinks, and rereams. The hammer then is ground and a slot is milled on one end. After the part is tumbled to remove burrs, the three sear surfaces are broached on a 36 inch vertical machine. Burrs resulting from the broaching operation are hand stoned to ensure their removal without breaking the sear edges. All work to this point is carefully inspected and the part

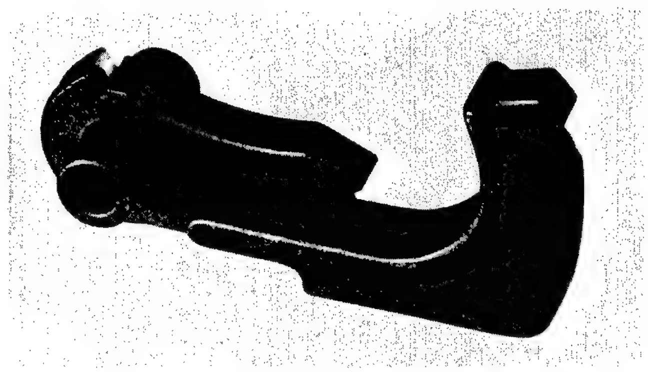


Figure 6

is case hardened to 77 on the Rockwell 30N scale to a depth of 0.016 inch. The surface then is cleaned by grit blasting and coated with a phosphate. A final grind on the sear notch, with the grinding burr removed by stoning, completes the part.

Overseas Production Funded Locally

Overseas licensing arrangements, which started in 1969, have been joint efforts. Colt has supplied technical information, a purchasing service to buy the necessary equipment, tooling, materials and supplies needed to produce the rifle, and training for the local work force. Each licensee has provided the building, the work force, and the money to pay for the entire operation, since they are the ultimate owners. Each agreement has been tailored to meet the specific needs of the licensee, with differing manufacturing philosophies accommodated in each case. However, standardized quality assurance procedures have been applied in all locations so that quality standards and required interchangeability have been preserved despite a range in maximum output of 20 to 1.

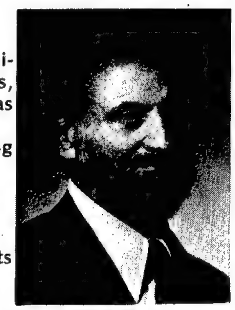
Group Technology Prime Factor

As an example of how the licensing programs have been implemented, 26 Korean engineers were trained in the United States—one for each important function in the production process. Colt then directed installation in the Korean plant of the best equipment practicable for the various operations and trained the work force in its operation. Group technology has been the prime factor in acquiring and arranging the manufacturing equipment in the foreign plants, with as much fabrication and inspection automation incorporated in the layouts as possible. Again, of prime importance, all inspection gages are identical and are used in the same manner regardless of location.

Fuze Power Supplies Tested in Lab

Artillery Firing Simulated

JOE RESTAINO is a Project Engineer in the Fuze Branch, Metal Parts Division, Munitions Production Base Modernization Agency. He has been active in fuze manufacturing projects for the past three years after working two years on the MPBMA's Kaiser study on plant equipment packages for the private sector. Mr. Restaino's expertise lies in the area of electronics components. He entered the Government program as a cooperative engineer trainee in 1970, working in the telemetry division. He received his B.S. in Electrical Engineering from New Mexico State University in 1973, then took his M.S. in Industrial Engineering from Texas A. & M. in 1975. He is a member of Eta Kappa Nu, honorary engineering fraternity.



HERBERT D. CURCHACK is Chief of the Test Technology Branch, Harry Diamond Laboratories. As part of the ERADCOM organization, this Branch includes Field Operations, Ballistic & Environmental Simulation. He has been with the organization since 1952 and has done research and development relating to servomechanisms, correlation techniques, transducers, shock tubes, plasma physics, optical interferometry, fuzes and fuze mechanisms, as well as (most recently) all aspects of analysis, investigation, and design of units and systems relating to ballistics and the Artillery Simulation Facility. Mr. Curchack received his B.S. in Engineering Physics in 1952 from NYU. He has done graduate work at the University of Maryland in Mathematics and Physics, attended special courses in plasma physics at Princeton; system response to shock & vibration at Brooklyn Polytech; and special orientation at the USA Field Artillery School. He has also organized and taught courses in Plasma Physics, Fuze Testing During R&D, and BASIC. Mr. Curchack has authored over twenty reports and has five patents. He received a Special Act Award in 1966, was the recipient of the Hinman Award for Technical Achievement in 1968, and was the HDL nominee in 1969 as the outstanding Handicapped Federal Employee of the Year. He is a Fellow of the American Association for the Advancement of Science; holds membership in the American Institute of Aeronautics and Astronautics, Sigma Pi Sigma, and the American Defense Preparedness Association; and is HDL's representative to the Aeroballistic Range Association.

Reliability of Army artillery fuzes has reached a new, higher level with the recent successful completion of a quality assurance program to test fuze power supplies. By simulating forces in an artillery tube, the Army can now test the functioning of fuze power supplies at a high spin rate in the laboratory. The high spin tabletop artillery simulator developed at Harry Diamond Laboratories to test the PS115 power supply for the M732 fuze is also useful for testing other power supplies.

Designed during an MM&T program for the U. S. Army Armament Command, Rock Island, Illinois, the tester provides the setback, angular acceleration, and centrifugal forces that are required to activate artillery fuze power supplies. Partially automatic, the tester also has a readout system for monitoring the power supply output voltage.

Activation Forces Duplicated

The PS115 and other artillery fuze power supplies are activated by three distinct forces acting in a specific sequence during the firing cycle. The first of these is the setback force. This is an inertial force that arises when components of a round—at rest initially—oppose their acceleration along the gun barrel. The second force is an angular force generated when the barrel rifling imparts a spinning motion to the round. These two forces combine to open the power supply ampule and release the electrolyte. Finally, the centrifugal force of the spinning round distributes the electrolyte to the cells to activate the fuze.

In the tester, a projectile housing the power supply is fired by an air gun into a spinning assembly that produces the required forces to simulate actual firing.

Testing Operation Utilizes Mitigator

The tester is seen in Figure 1 and diagrammed schematically in Figure 2. In testing, the power supply is loaded into the cylindrical test projectile, which in turn is placed in the air gun breech. The projectile seals the breech end of the gun by bearing against an O-ring and is held back by a metal dowel or release pin. A thin plastic diaphragm seals the air gun muzzle end. Air is pumped from the gun and the release pin is withdrawn, allowing ambient room air pressure to push and accelerate the projectile along the gun barrel. The projectile ruptures the plastic diaphragm and enters the spinner assembly.

The spinner assembly contains a rotating catch tube with an inner diameter slightly larger than the projectile diameter. Inside this tube are a mitigator (an energy absorbing, crushable mass) and behind it a solid brass cylinder called a momentum exchange mass (MEM).

Figure 1

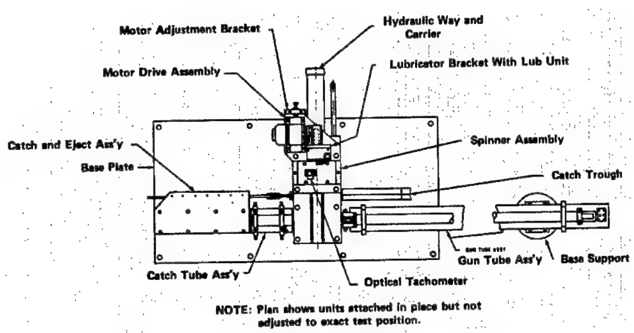


Figure 2

These items bring the projectile to an abrupt but controlled stop, imparting both the setback force and the angular acceleration (by imparting the spinning motion of the assembly to the projectile). Setback forces up to 5000 g and spin rates of 300 rps can be produced. The centrifugal force of the now stationary, but spinning, projectile completes activation of the power supply. The MEM, having played its role by absorbing the projectile momentum, is ejected from the spinner assembly into a catch tube and has no further role in the test.

With the power supply thus activated, two spring loaded electrical contacts on the outer projectile surface are released to contact copper coatings on the inner surface of the spinner tube. The coatings are connected to a voltage monitor. The spinner tube usually rotates for about three minutes to monitor the power supply output. The mechanisms of this operation become clearer when we consider the function of individual components in greater detail.

Grabber Pins Impart Spin

The two piece projectile shown in Figure 3 is made from a linen base phenolic. The two sections screw together. The projectile is 2.009 inches in diameter, 3.06 inches long, and weighs 8.96 ounces.

Figure 3

All electrical connections to the power supply are contained in the forward section into which the power supply is mounted. The spring loaded electrical contacts are on the outer surface of this section. These contacts are retracted until the projectile begins spinning during the test. The two metal studs on the front end of the projectile, called grabber pins, are instrumental in imparting the spinning motion. When the projection contacts the spinning mitigator-MEM combination in the spinner assembly, these pins penetrate the mitigator surface, coupling the projectile and imparting the high angular acceleration to it.

The rear section of the projectile is essentially a cover. The projectile is assembled for testing by hand but usually becomes tightly locked during testing and must be disassembled using a tool. The projectile is reusable—with proper care it can be fired several hundred times.

Air Gun Manual or Auto

The air gun is a smooth bore aluminum tube 84 inches long with a 2.012 inch ID and 2.50 inch OD. It is supported by an aluminum I-beam. The gun may be operated either manually or automatically. In the automatic mode, two microswitches near the breech contact a vacuum valve in the pipes connecting the gun tube to the vacuum pump. The vacuum valve opens to draw air out of the gun tube only when just the switch nearest the breech is depressed. This comes about as follows.

After the mylar diaphragm is inserted to seal off the muzzle, the projectile is inserted into the breech, depressing both switches. When the projectile is pushed forward against the release pin, pressure on the rear switch is relieved, leaving only the front switch depressed. This opens the vacuum valve and evacuation of the gun tube begins. When the gun is fired following evacuation, the front switch is released as the projectile moves forward. The valve again closes and the vacuum system returns to the preload state. In the manual mode, a switch operates the vacuum valve on demand.

Spinner Assembly Scans RPS

The spinner tube is a hollow fiberglass cylinder 11.7 inches long with an inner diameter of 2.012 inches (the same as that of the air gun barrel) and an outer diameter of about three inches. For test operation, the air gun and spinner tube are carefully aligned.

The inner surface of the spinner tube has two semicylinders of copper plating 10.7 inches long for electrical contact from the projectile to the voltage monitor. Insulated from each other by two narrow strips of fiberglass, these semicylinders are connected through the wall of the tube to a pair of slip rings on the outer surface. Carbon alloy brushes bear against the slip rings to complete the circuit to the remote monitor.

A scanner band on the outer surface of the spinner tube is used to measure rotational speed of the tube during testing. This metal strip has ten reflective and ten dull areas alternating around its circumference. A photoelectric sensor viewing a light beam reflected from the band generates a series of ten pulses during each rotation of the spinner tube. An electronic counter connected to the sensor indicates speed in revolutions per second.

Control Console Provided

Nearly all of the electrical controls needed to operate the tester are contained in a control console. When operating in the automatic mode, an electrical timer is used to properly sequence many of the test operations. However, the power supply voltage monitor and the electrical counter for rotational speed are separate from this console.

Mitigator Preserves MEM

In an elastic collision between an MEM and a projectile of equal weight, the projectile would come to a complete stop within the spinner tube with all of the kinetic energy of the projectile transferred to the MEM, which would be ejected from the tube. However, if the impact were not completely elastic, some of the kinetic energy would be absorbed in crushing, with permanent damage to the projectile. For this reason, the mitigator was introduced.

The mitigator consists of 7 ply, 0.75 inch thick triangular plywood blocks. Each mitigator contains six such blocks taped together with fiberglass reinforced tape. During impact, the mitigator deforms, thus limiting the peak force on the projectile and leaving it intact. A fresh mitigator and one deformed during testing are shown in Figure 4. A new mitigator is used for each test.

Also shown in Figure 4 is an MEM, a solid brass cylinder 1.75 inches in diameter and 4.12 inches long. The MEM has four phenolic runners fastened to its surface which are machined to an overall diameter of 2.009 inches. The use of runners on an undersized cylinder keeps the MEM from acting as a piston. In that role, it might draw the projectile with it from the spinner tube following impact. The runners are periodically checked for wear and replaced before the MEM becomes loose in the tube. The MEM weighs 45.5 oz.

The mitigator and MEM are in contact in the spinner tube prior to impact, with the mitigator located a specific set distance from the spinner tube entrance. This distance is 2.5 inches for the elements used with the PS115 power supplies.

NDT Brings Dollar Savings

The high spin tabletop artillery simulator can be adapted to other fuze power supplies to ease their testing, and already has been used to test PS127 power supplies. Wide further use of this device will enhance fuze reliability and preclude the use of more expensive (destructive) test procedures. Vast savings of munitions dollars will result from this manufacturing technology project.

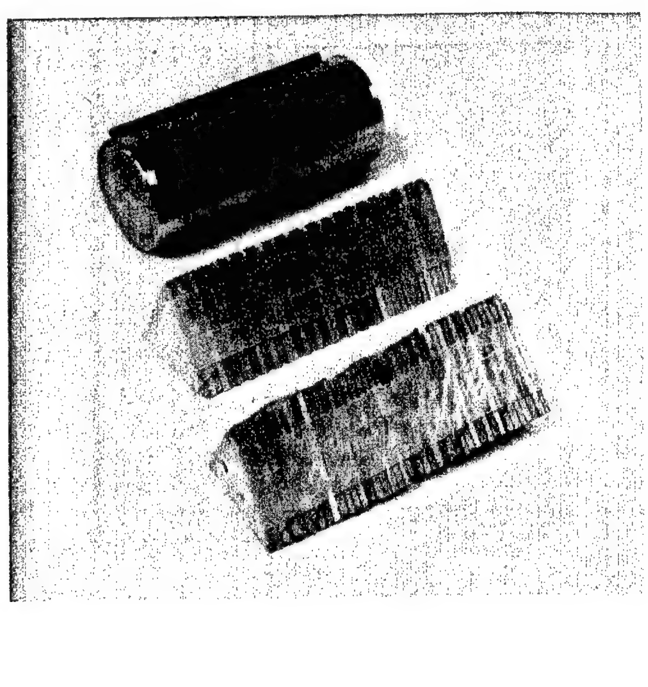


Figure 4

Automated Process Attractive

Propellant Injection Molded

HENRY C. ALLEN is a Research Chemist in the Propulsion Directorate, USAMICOM. He received the B.S. in Chemistry degree from the University of Georgia in 1954. He was employed by the Chemstrand Corporation for six years in research on fiber-forming polymers. He joined MICOM in 1960, and has specialized in polymeric components of rocket motors, particularly solid propellant binders. He has authored and coauthored 16 papers and ten patents since joining MICOM.

Work at Atlantic Research Corporation has demonstrated the feasibility of loading quick cure propellants into small rocket motor cases by injection molding. As a result, production equipment is now being built to load VIPER trainer rounds. With automation of conventional processing steps, man-hour savings of better than fifty percent are projected when compared with earlier volumetric fill techniques.

While conducting an MM&T program for the Army Missile Command, Atlantic Research engineers used a modified HTPB (hydroxy terminated polybutadiene) propellant to produce injection molded motors. The effort included design and fabrication of prototype automated injection molding equipment and successful production of live motors. Injection molding took about five minutes and propellant cure another five minutes. The injection time can be even shorter for smaller motors, depending on the amount of propellant loaded and its grain web thickness. Injection molded motors have performed satisfactorily in static firing and ballistic testing.

Propellant Requirements Met

To meet program requirements, Atlantic Research needed an HTPB propellant composition that:

- Was compatible with the injection molding process
- Had a solids loading of at least 86 percent
- Had a burning rate of at least 0.5 inch/sec at 1000 psi
- Would cure quickly.

On the basis of these requirements, they selected ARCADENE 360, composed of 39.0 wt. percent 90 μm ammonium perchlorate, 30.0 wt. percent 5 μm ammonium perchlorate, 18.0 wt. percent 30 um H30 aluminum, 12.0 wt. percent HTPB/isophorone diiosocyanate (IPDI) as a binder and curative, and 1.0 wt. percent iron oxide as a burn rate modifier. To achieve the quick cure properties required, they modified this formulation by adding a cure accelerator composed of 0.05 percent triphenyl bismuth, 0.1 percent magnesium oxide, and 0.05 percent maleic anhydride. The triphenyl bismuth enhances the cure rate, while the maleic anhydride reacts with the polymer to generate the acid needed to promote this enhancement. The magnesium oxide acts as a scavenger to retard premature gelation. The modified ARCADENE 360 propellant cures sufficiently in three minutes at 300 F for removal from the mold without structural damage to the grains. Required mechanical properties can be obtained by postcure for 24 hours at 145 F.

Molding Apparatus Temperature Controlled

Figure 1 is a general layout of the apparatus used to demonstrate the feasibility of injection molding propellant grains using the quick cure formulation. The mold assembly is mounted on a bar that is moved along the frame rails by the hydraulic cylinder. The propellant injection cylinder is a jacketed sleeve that contains an aluminum tube of vacuum cast propellant. For injection, a nozzle at the top of the tube is attached to the motorcase/mold assembly and a Teflon piston at the bottom of the aluminum tube is pushed up by the shaft of an air cylinder. Water circulating through the jacket insures a constant propellant temperature in the tube. The propellant cylinder pivots to one side to clear the mold assembly when the mandrel is removed from the motorcase.

The mold assembly, shown in Figure 2, was designed for a steel motorcase with a cylindrical mandrel. Both the mold and mandrel are bored for heating and cooling by hot oil and cold water, respectively. The mold is split lengthwise to allow installation of the motorcase. The mandrel, installed from the open end, has a plastic covered plug on its tip that is recessed during filling. Air pressure forces this tip forward against the motorcase during cure to give the forward end of the case the desired shape.

Thermocouples Most Effective

To control the process, instrumentation was designed to sense and record motorcase temperature, propellant temperature in the injection nozzle, propellant pressure in the injection nozzle, and propellant pressure in the motorcase when full. However, the pressure transducers did not respond well and ultimately were not used. On the other hand, the two thermocouples, located as shown in Figure 2, provide very quick response to changes in temperature. Temperature observations clearly indicate when propellant is flowing through the injection nozzle and when it has stopped. Filling of the motorcase is also clearly monitored by watching the temperature.

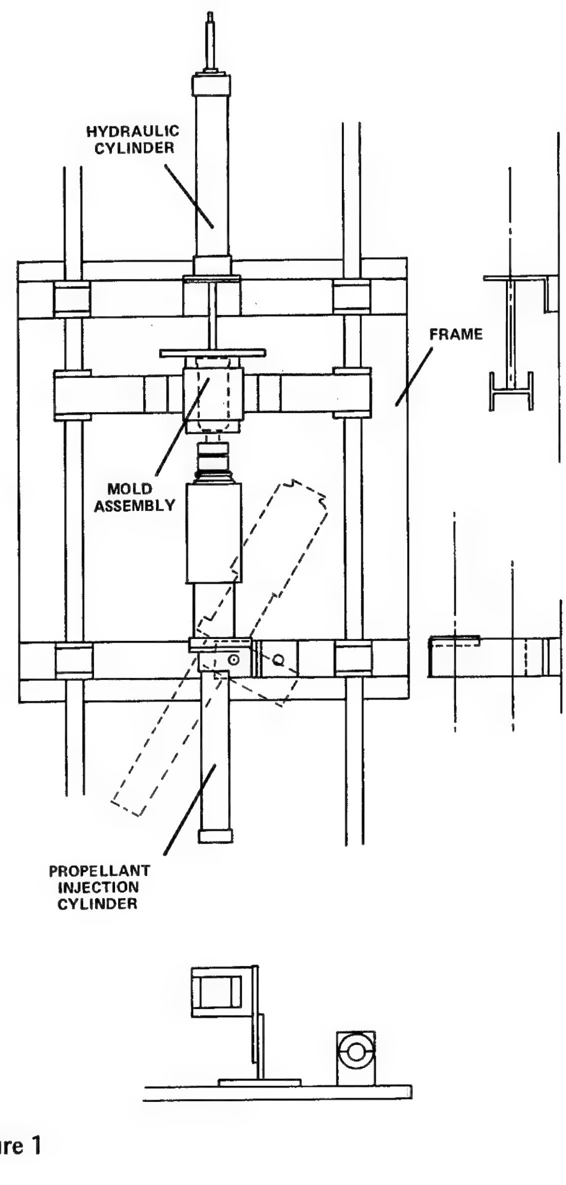


Figure 1

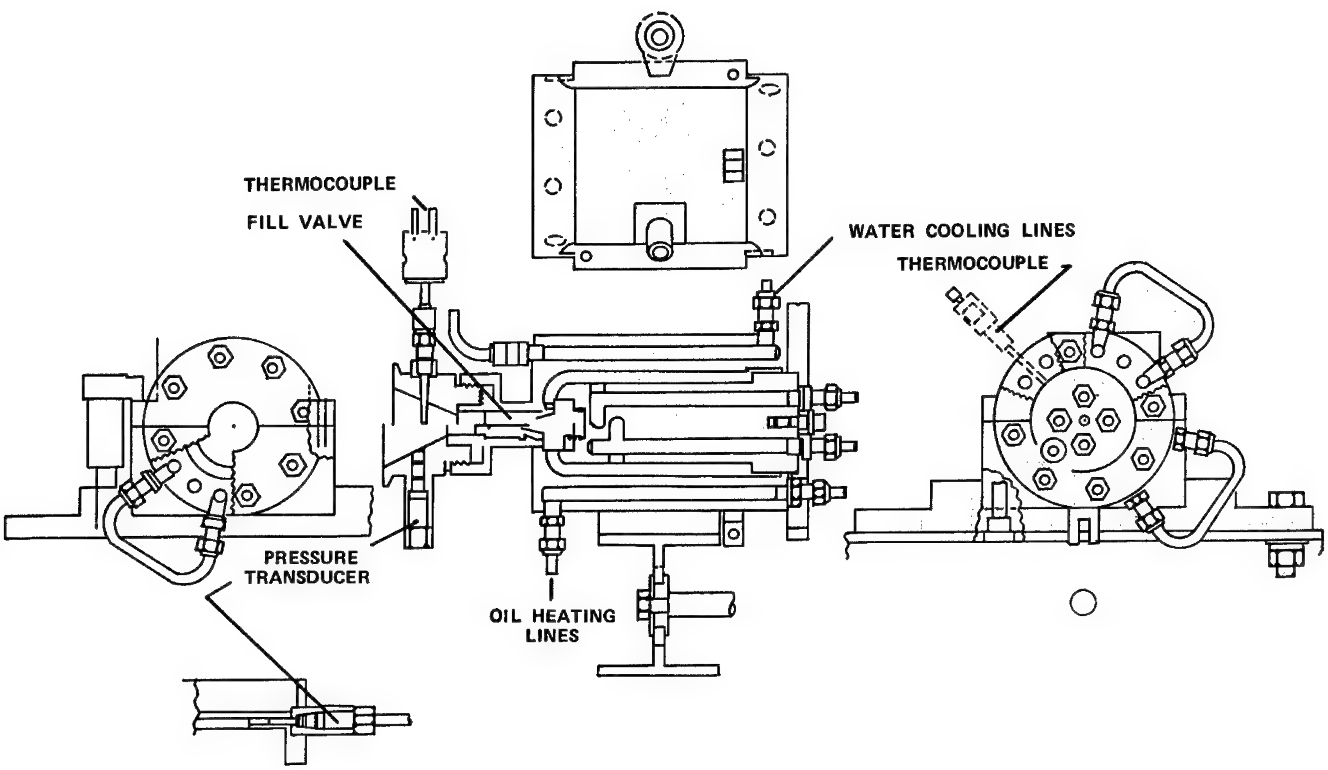


Figure 2

Test Runs Successful

In a series of test runs with this equipment using an injection pressure of 80 psi, injection times were mostly in the range of two and one half to five and one half minutes. The propellant mass loaded was about 0.5 lb. per motor. Both curing and cooling of all units took five minutes. The cure time was based on a thermal analysis prediction of two and one half minutes required to elevate the center of the web to the cure temperature and on the results of laboratory tests that indicated good propellant physical properties after five minutes at 300 F with some postcuring. Quantitative examination of propellant cured in the motorcases for five minutes indicated a complete cure—firm, hard propellant at both ends.

Cooling time was based on the motorcase thermocouple temperature reading and on the propellant and case being fully cool to the touch after removal from the mold. A cooling time of approximately two minutes is possible when the changeover to mandrel pull is remotely automated. That time, coupled with a five minute cure time and a two to three minute fill time, would very closely approach a nine minute cycle time for a ¼ inch thick web. Thinner webs would require shorter cycle times.

Motors containing the injection molded grains performed acceptably in static test firings. Furthermore, ballistic data variability was about the same as that obtained from firing normally filled and cured motors.

Machine Design Based on MM&T

Based on these feasibility tests, a prototype injection molding machine was designed as shown in Figure 3. The machine is mounted on an open frame structure and hydraulically operated by a manual remote control system.

Production equipment for the VIPER trainer based on this prototype equipment—a direct result of the MM&T project—is now being built. The production machine will mold six units per operation and will have a machine cycle time of about five minutes. Projections indicate that production costs with this method will be approximately 0.046 man-hours/unit. Costs on the originally planned production loading technique utilizing a volumetric fill technique were projected at 0.096 man-hours/unit. Thus, production costs should be at least fifty percent less with the automated injection molding process.

Wider Application Possible

Atlantic Research's MM&T program has clearly demonstrated that injection molding is a feasible process for manufacture of HTPB propellant grains and that substantial cost savings can be realized. The use of a three component cure catalyst system to modify ARCADENE 360 provides a quick during HTPB propellant that is adaptable to the process. Although injection molding is being implemented only for the VIPER training rounds at this time, the program has demonstrated that it is a feasible production method for any small rocket motor where adequate openings are available into the case. In addition to the demonstrated production cost savings, the large hardware inventory associated with conventional processing and cure technology will be eliminated. Energy costs will also be reduced, thanks to the very short cure cycle.

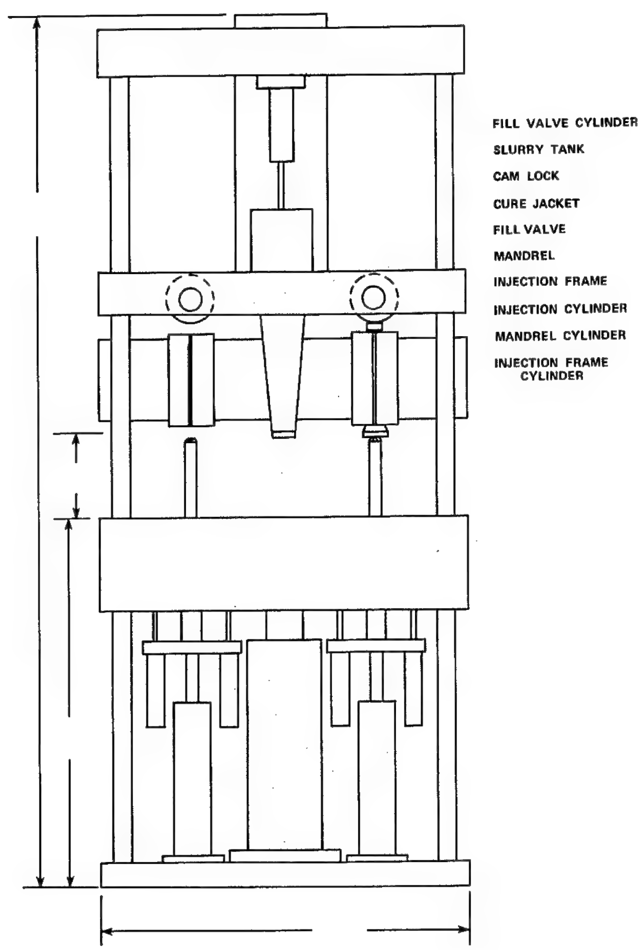


Figure 3

$860 Million Savings Possible

Computerized Proces

A discounted cash flow analysis of computerized process planning technology will yield potential savings of $130 million in defense procurement for fiscal years 1978 through 1987, according to a United Technologies study conducted for the U. S. Army Missile Command. This projection is based on 15 percent utilization of the procedure by the defense industry.

Government and industry objectives to reduce costs or alternatively improve productivity have led to widespread interest in computerized process planning. After several years of research and development activity, computer systems in process planning are finally beginning to emerge.

Worldwide Interest

Throughout the world, current advancements in computerized process planning technology are being viewed as merely the first phase of an advanced process planning technology that will eventually remake industrial production systems.

Interest in programming computers to generate process plans for manufacturing parts is worldwide and involves private industry, universities, and governments. In recent years the interest has intensified due to an increasing awareness of what computers can do for labor intensive methods of process planning and manufacturing in general. Process planning procedures that depend exclusively on skilled or trained production labor are vulnerable to delays, errors, and higher than necessary production costs. Dependence on such methods often precludes a thorough analysis and optimization of the process plan and nearly always results in the nonstandardization of processes.

Unfortunately, the complexity of machined parts process planning has resulted in computerized process planning remaining in the conceptual stage for some time. The benefits are anticipated, but the path to follow has been unclear.

To date, the major effort has been to fully understand the variables of process planning and to develop an approach that systematically incorporates all aspects of the planning process. Computerized process planning is highly modular and provides the overall framework to plan production methods for machined parts. The result has been the development of a base system into which scientific principles of metalworking and workshop practice are easily introduced.

Previous Programs Narrow in Scope

There have been several notable projects on computerized process planning since the late 1960's. Much of the early work originated in Sweden, Norway, and Germany. In general, these systems, such as SINTEF's AUTOPROS and systems developed by Aachen University, contributed significantly to the present level of understanding, but proved to be too limited in scope. Other projects like EXAPT and GETURN were also of interest, but they primarily provided detailing of numerical control operations after much of the required process planning was finished. In the United States, much of the current work is directed toward the development of data processing systems capable of storing and retrieving process plans by coded methods. Although these systems offer benefits of standardization, they do not address the problems of generating process plans or economic analysis of the process.

Generative Approach Complex

In general, the technology of computer process planning can be characterized by differentiating between the basic technical approaches that have been advocated. The highest level of differentiation divides the technology into the "variants" and "generative" principles. The first is based on storing standard process plans in the computer for specified families of parts. Using a part

RICHARD A. KOTLER is Manager, Manufacturing Technology, Engineering Directorate of the U. S. Army Missile Command. After joining MICOM following his graduation in 1967 from Tennessee Technological University in Industrial Engineering, he has held continually more responsible positions in numerical control and computer aided manufacturing programs, printed circuits, and hybrid microcircuits; he is a member of the International Society for Hybrid Microcircuits. He received his MBA from Vanderbilt this past year, and serves as Coordinator of Command MICOM Manufacturing Methods and Technology programs.

Planning – Part 1

classification coding technique, process plans can be retrieved and varied for a new part. This approach partially automates the conventional procedure of using an existing process plan to produce a new plan. The concept is based on similarity of fabricated components. The CAPP system being developed by CAM-I is a system based on the variants principle.

The generative approach is more complex because the computer must be capable of making process decisions. The idea is to provide enough intelligence about metalworking to allow the computer to generate a sequence of operations and detailed operation plans. This kind of system requires detailed input about the part design. From this input, the generative system determines the sequence of stock removal operations; selects machine tools, cutting sequences and cutter tools; and determines machining parameters of feed, speed and depth of cut. Additionally, generative systems provide some optimization of the process plan by basing decisions on the analysis of production cost and/or rate.

Process Planning Key to Manufacturing

Process planning is the key activity which determines how a product is to be manufactured. Process planning, in fact, is the first step in manufacturing. There are several levels of process planning activity. Early in product engineering and development, process planning is responsible for determining the general methods of production. In the last stages of design, part design data is transferred from engineering to manufacturing and process planners develop the detailed work package for fabricating the part.

Process planning is a major determinant of the cost of machined components. It determines the sequence of operations and utilization of machine tools. Cutting tools, fixtures, gages, and other accessory tools are specified. Dimensions and tolerances are determined for each stage of forming the workpiece. Feeds, speeds, and other parameters of a metalcutting process are determined. Requirements for special processes, such as nitriding and plating, are determined and the production methods specified.

CPPP Technology Utilized

Computerized Production Process Planning (CPPP) is a process planning system developed for the Missile Command by United Technologies Research Center (UTRC). A top down decomposition of the CPPP system is shown in Figure 1. The system assists process planners in planning the production of machined cylindrical parts. Through the use of automatic and semiautomatic means, CPPP generates a summary of operations and the detailed operation sheets required by the workshop. Operation sheets include sketches of the fully dimensioned workpiece with tolerances. Machine tool, cut sequences, tools, and machining parameters are also specified.

CPPP is a first system aimed at developing an advanced technology to plan and control the cost of machined parts. The immediate objective has been to develop a system which will standardize the production process by automating the planning activities. It was also an objective to develop a system that could be used to analyze and evaluate process alternatives. Later enhancements to the technology could provide for optimizing the process and would address noncylindrical parts as well as cylindrical parts. The basic concepts of CPPP apply in principle to all machined parts.

Models Account for Variances

Salient features of CPPP technology are process decision modeling, geometric modeling, production cost and rate analysis, dimension and tolerance analysis, and man/machine communication. Process decision modeling is a technique developed by United Technologies to specify the manufacturing rationale associated with the produc-

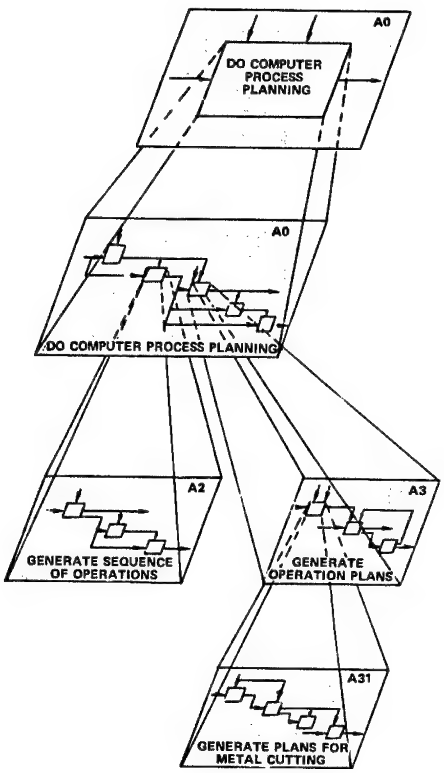


Figure 1

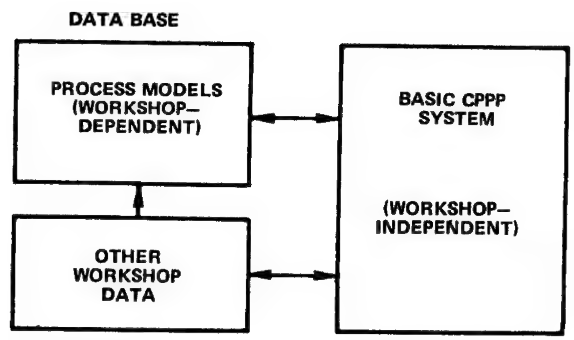


Figure 2

tion of part families by a manufacturer. Process models are input to the data base and are used by CPPP to make decisions in generating sequences of operations. The models account for variances in part material, geometry, and special process requirements. A computer process planning language called COPPL and a language processor were developed to support the implementation of process models. This provides the capability to implement CPPP in any manufacturing environment. Figure 2 illustrates the CPPP implementation concept.

Large Data Base Required

In addition to process models, the manufacturer must develop a large data base when implementing CPPP. Machine tool descriptions, types of cuts made by machines, cutter tools, stock removal and tolerance data, and machinability data are needed. Complete part design information must also be stored in the data base. CPPP requires information equivalent to the blueprint to generate a process plan. Material, shape, dimensions, tolerances, form conditions, surface finishes and special process requirements must be specified.

CPPP does not depend totally on automatic methods of generating process plans. An extensive man/machine interaction system can be used by process planners to review or modify process decisions made by CPPP. Metalcutting and nonmetalcutting operations and sequences can be defined. Also, detailed operation data such as machine tools, cut sequences, tools, and feeds and speeds can be specified.

CPPP Implemented

CPPP was developed and implemented as a demonstration system to show how a process planner working at a graphic display terminal would develop a process plan for a nitralloy sleeve. A process model and data base were developed for a part family of nitralloy sleeves manufactured by the Hamilton Standard Division of United Technologies. The family includes components of the JFC78 Fuel Control for the General Electric T700 engine, which was selected to power the Army UTTAS helicopter being developed by Sikorsky Aircraft.

The demonstration part is made from AMS6470 bar stock and has requirements of nitriding to produce case hardness. The part family consists of parts with complex ID and OD geometry with cylindrical and noncylindrical features. Part sizes are up to six inches in length and diameters up to two inches. Surface finish requirements are very smooth and roundness, straightness, and taper form conditions are tight. The part family is of a complexity that manufactured components can require up to 40 operations.

The demonstration revealed that advanced computerized process planning is technologically feasible and the

CPPP system can be implemented for any manufacturer of machined cylindrical parts. It shows also that CPPP reduces process planning labor and lead time, provides benefits of process plan standardization, and can be used to evaluate process alternatives. Also, it shows that process planners can effectively communicate with the computer to perform a variety of process planning activities.

Technological Objectives

United Technologies Research Center initiated its research of computerized process planning technology with several objectives in mind. First, the computer system developed must be adaptable to any manufacturer of mechanical parts. Secondly, UTRC believed that a CPPP system should be capable of generating alternative solutions to a process problem and then pick the best. Thirdly, UTRC believed it important that full part design information be available to the system. Finally, it was felt that totally deterministic systems would not be developed for a long time. There would always be situations where manufacturing would want to influence or change computer decisions or provide data that is missing in the system. Therefore, an extensive man/machine interaction capability had to be developed.

Software System Overview

CPPP is an integrated system of software modules. A high level diagram of the system is shown in Figure 3. There are seven principal components, as follows:

- The Data Input System
- The Language Processor System
- The Data Base
- The Process Decision and Analysis System
- The Vocabulary and Cut Application System
- The Interactive Display System
- The Process Plan Output System.

The data input and language processor systems provide a manufacturer with the means to build the large data base required by CPPP. The data base must be developed to contain descriptions of the workshop's machine and tool resources, stock removal allowances for cutting materials, tolerance information with respect to cutting situations, machinability information and process decision models. To use CPPP, it is also required that process planners first enter the part design into the data base.

CPPP requires part design data equivalent to the information content of a blueprint. This includes part shape,

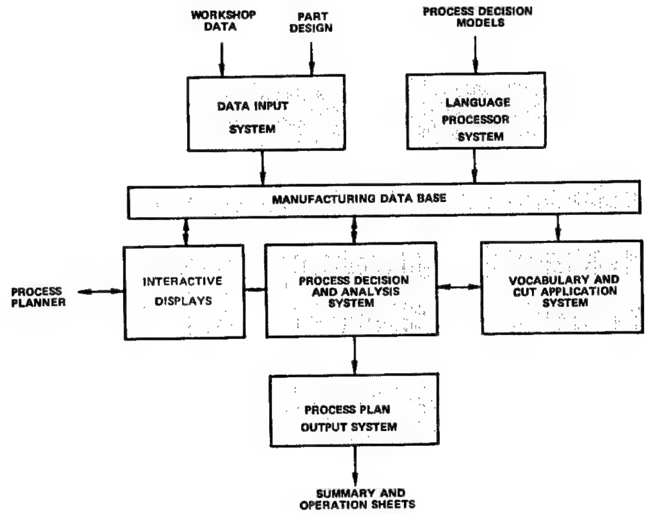


Figure 3

dimensions, tolerances, surface finish, geometric form conditions, material specifications and any requirements of surface treatment or coatings. In addition to the part design data, the raw material (bar, casting, forging, extrusion) to be used must be identified and geometrically described.

Simplified Machine Language

The language processor system is used to input to the system the process decision models of different part families. Process planners will use the computer process planning language (COPPL), developed under the Army contract, to program the logic of process decision models. The programmed models are converted into a computer readable code by the language processor and then stored in the data base. Process planners using the COPPL language do not require computer programming skills. The language is more of an English-like language than a computer programming language. This has resulted from the objective to develop COPPL so that it could be used to document or newly specify a manufacturer's process rules. Therfore, the language can be easily read and understood by manufacturing people.

The COPPL language allows the process planner the freedom of choosing vocabulary when formulating process decision models. This eliminates restrictions on the process planner and provides the flexibility to express the

rationale for fabricating part families. For example, the process planner can use terms like the following: deep hole, free end, open diameter, exposed, counterbore, groove, chamfer, true position, diametral tolerance, surface finish, etc. When these terms are used in programmed expressions of a process model, such as:

Turn outside surface on manual lathe if surface is an open diameter, (and) diametral tolerance is $\geqslant 0.002$ $,

they have a specific meaning. A simple computer code must be written for each vocabulary term so that CPPP can interpret the programmed expression. These computer codes are easily added to the CPPP system through the vocabulary and cut application system. In the preceding example, the code for "open diameter" would test a part surface description to determine if it is an open diameter.

Vocabulary Needs Reduced

The requirement to develop vocabulary codes reduces significantly after process models have been implemented for one or more part families. Much of the vocabulary used by a manufacturer would be defined after the first few part families. Vocabulary programs could also be standardized and implemented for multiple manufacturing firms.

CPPP also allows a manufacturer to define the type of cuts that a machine tool can make. Each type of cut requires a simple computer code to be added to the CPPP system as is done for the vocabulary programs. In general, the type of cuts that can be made by a machine are based on the type of machine tool. If the same cut can be made on multiple machine tools, it can be indicated in the machine tool data base.

The process decision and analysis system, the interactive display system and the process plan output system combine to form the nucleus of the CPPP system. These components are independent of any manufacturer or part families. The process decision and analysis system is the "heart" of the process planning capability. It contains the modules to retrieve the part design data and the process models from the data base and provides the main subsystems for generating the sequence of operations, planning operation details (machine tools, cut sequences, tools, and machining parameters) and calculating workpiece dimensions and tolerances. Included in this part of the system is the module that interprets the coded form of the process model.

The interactive display system consists of all the modules supporting communications between a process planner and CPPP. There are multiple interaction points at which the process planner can review or modify decisions made by CPPP. Additionally, displays are used to initiate and terminate the CPPP system and to provide information from the data base.

Process Planning Detailed

Figure 4 shows a high level view of the three primary process planning functions of CPPP. They are organized to produce a process plan in three distinct and separate steps. The first step generates the sequence of operations. It begins when the process planner inputs a part number to the system. The part number is used to retrieve the design data from the data base. The raw material description specified by the manufacturer for the process would also be retrieved with the part design data. CPPP does not select the raw material; this requirement must be determined outside the system and identified in the data base. Also contained in the design data is a classification code identifying the part family to which the part belongs. This code is used to retrieve the appropriate process model from the data base. The code can be designed to provide any level of classification desired by the manufacturer. In the demonstration system, part families are primarily broken down by function, such as compressor seals, valves, and sleeves.

The sequence of operations is generated with the process model alone or by a combination of the model and process planner interacting with the system. The model is programmed to determine a sequence of operations based on specific geometry and material characteristics found in the part design data. The generated sequence would contain both metalcutting and nonmetalcutting operations. Additionally, the specific part surfaces

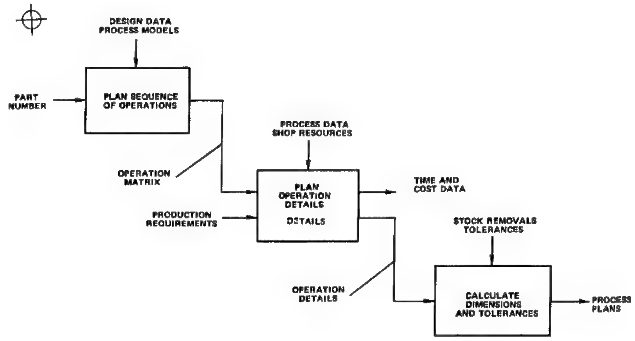


Figure 4

or features cut in an operation would be identified. Also, part surfaces requiring special processes such as nitriding or plating would be identified with the operation.

Results of the initial planning function are stored in the data base in the form of an operation matrix. The matrix is organized so that complete summary information is known about any operation or part surface. The data is used by subsequent planning functions to determine what the workpiece should look like after each operation. For example, the matrix specifies for each part surface the types of operations required to transform the raw material to a finished part.

Detail Planning Function

The second planning function generates the details of each operation defined in the operation matrix. The task here is to select machine tools, cut sequences, and cutter tools and to determine feeds, speeds, cutting depths, and number of cutting passes. There are many variables and interdependencies in making detail decisions of the above type. Therefore, an analysis procedure has been developed to evaluate alternative combinations of machine tools, cut sequences and cutter tools for each operation. The best combination is based on optimum production rate or cost performance. As in the first planning function, the process planner has the option to interact with CPPP to review or modify decisions made.

The detail planning function is factored into the subfunctions identified as follows:

- Determine candidate machine tools
- Determine candidate cut sequences
- Determine types of cuts
- Select candidate cutter tools
- Determine machining parameters
- Determine production rates and costs
- Select best combination of tools
- Select best machine tool and cut sequence

The manufacturer must provide several kinds of data to support planning of operation details. The data required includes machine tool descriptions, the types of cuts made by machines, stock removal allowances, preassigned cutter tools, and machinability data. Additionally, the process planner must specify the approximate lot size and production criterion to use in the analysis.

The output generated by the detail planning function consists of detailed operation descriptions and production time and cost data. The operation data is stored in the data base for subsequent use in calculating dimensions and tolerances.

The third planning function calculates the actual workpiece dimensions and tolerances for each operation. Prior to this step the system works only with nominal values. Therefore, this function also serves to ensure the part can be made within tolerance by the process plan. A salient characteristic of this function is the use of tolerance chart procedures for analyzing tolerance buildup and calculating dimensions. To do the analysis and calculations, the manufacturer must provide stock removal allowances and tolerance data. The output produced is used to generate operation sheets with dimensioned workpiece sketches.

Hardware System Overview

The hardware required by the CPPP system consists of a general purpose computer with common peripheral devices, a graphic display terminal, and a hard copy line plotting device.

The CPPP system was developed on a general purpose computer of the UNIVAC 1108/1110 class. Modification for use on such general purpose computers as the IBM 360 and 370 models can be accomplished with relatively little effort.

As currently segmented, CPPP requires about 60,000 words of computer memory. This requirement can be reduced or increased by varying the software organization. The computer memory requirement is somewhat dependent on the complexity of the process planning problems to which the system is applied. Complex part families and process plans require more memory than simpler ones.

Disks or other direct access devices are required to store the CPPP system and the manufacturing data base. The system itself requires about 550,000 words, if source (symbolic) and object (relocatable) code are stored. If only the load module (absolute code) is stored, about 60,000 words suffice. Storage requirements for the manufacturing data base will, of course, vary widely. The smallest viable data base will require a few hundred thousand words while very large manufacturers will require millions. It would be practical to use magnetic tape, rather than direct access storage, for roughly half of the data base.

The CPPP user interacts with the system via a low cost graphic display terminal. The system has been implemented for TEKTRONIX 4006, 4010, 4012, and 4014 terminals with 021-0074-00 Optional Data Communications Interface or its equivalent. A full duplex transmission rate of at least 1200 characters per second is recommend-

ed. (Slower rates may be used, but noticeably degrade system performance.) Software support is the TEKTRONIX PLOT-10 Terminal Control System and Standard FORTRAN Subroutine Package.

A line plotter is used to generate workpiece sketches for hard copy process plans. CPPP currently uses a CalComp plotter with a local software package. Conversion to use other line plotters and/or software packages can generally be accomplished with little effort.

Part Characteristics Determined

To develop a sequence of operations for a machined part, a process planner considers the part shape, dimensions, tolerances, finish and material requirements, and special process requirements. The process planner prepares himself for the task by organizing his thinking in accordance with some key characteristics of the part to be fabricated.

For example: the part is cylindrical and is made from bar stock of AMS 5630; it has a thru bore; L/D is less than 2.0; tolerance requirements are less than .001; surface finish requirements are less than 16; etc. Based on such information, the planner calls on his experience to formulate an overall production approach. CPPP provides a similar approach to generate process plans.

Family of Parts Classification

Generally speaking, a part design can be examined in the computer by automatic means and operation requirements for each surface determined based on the theoretical capabilities of various production methods and the initial raw material state. A more difficult problem, however, is sequencing the operations. The sequence is based on machine tool capacities, operation precedence, and process requirements. The latter includes requirements to machine locating surfaces. CPPP currently deals with the sequencing problem by developing process models for families of parts. A manufacturer is able to formulate process logic for part families more easily because there is only a finite number of design characteristics to consider and there is only a finite number of design characteristics to consider and there is usually the process experience to draw on.

CPPP allows the manufacturer complete freedom to define part families. Figures 5 and 6 show four different part designs. They are all sleeve components used in fuel controls. The part geometries are quite different. The two parts of Figure 5 are made from nitralloy bar stock and require special processes of nitriding, copper and

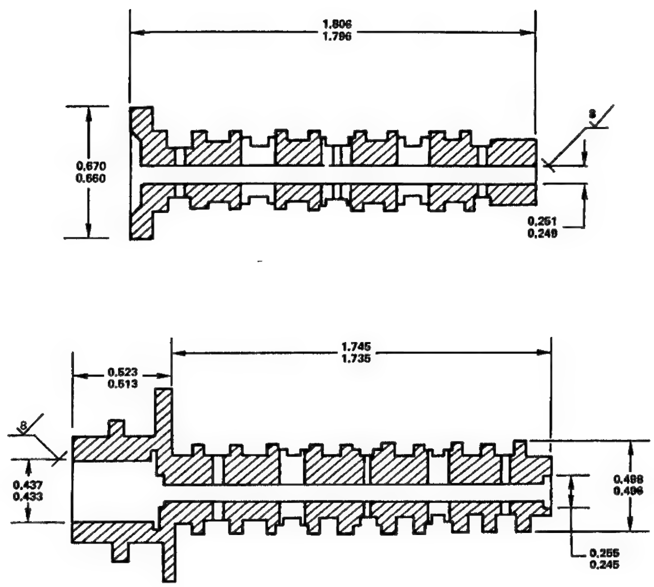


Figure 5

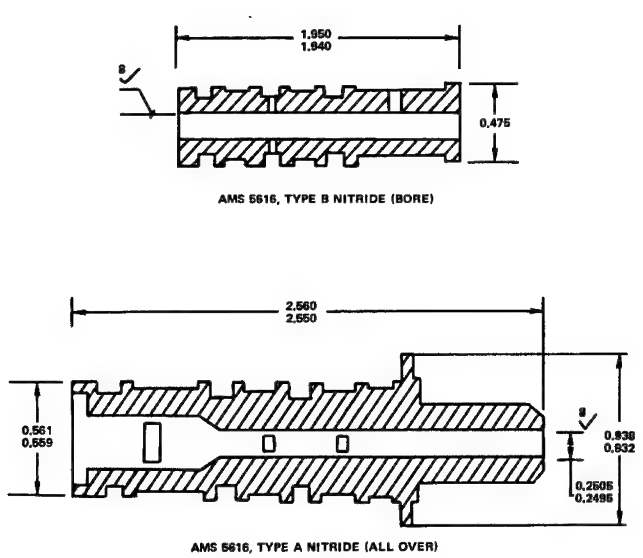


Figure 6

nickel plating and electrofilming. The parts of Figure 6 are made of AMS 5616 steel. The sleeves normally do not exceed six inches in length or two inches in diameter. They have tight tolerances and finish. They may have thru bores. Each of these parts require a nitriding process different from the parts of Figure 5 and different from each other. In one case, Type B nitride is required and in the other Type A nitride. The processes involved are quite different.

The grouping of sleeves into part families for purposes of defining process models can occur in several ways. The sleeves of all four types could be classified as one family. In that case, it would be necessary to 'code' all parts as 'sleeves' and one process model would be defined for all possible geometry, material and process variations. This would be a fairly complex model. Another approach would group nitralloy sleeves and AMS 5616 sleeves of Type A and B nitride into their own respective part families. This would classify parts primarily by process—the process models would then be required to accomodate shape and geometry variations.

Process Models Formulated

The process model for a part family defines the rationale for determining a sequence of operations and specifying particular part surfaces affected by each operation. To develop a model, the manufacturer first formulates a general process for the specified part family. The general process is simply an outline of the steps that may be required to fabricate a particular part of the family. Process steps must be included for any variation allowed by the part family definition. For example, if deep hole drilling is required for some parts and not for others, the process model must provide for the possibility. Similarly, if the part family has large variations in surface and finish requirements, types of features, or special process requirements, the process model must allow for them. The following is an outline of the general process for nitralloy sleeves:

- Draw material
- Shape bar stock
- Install deep hole
- Complete shaping
- Hone and/or grind for form conditions
- Finish turn
- Install grooves by crush grinding
- Install noncylindrical features
- Harden by nitriding and plate surfaces
- Install remaining noncylindrical features
- Finish machine
- Harden by type A nitride
- Finish to prenitride size
- Inspect, clean, mark, electrofilm, preserve and pack part.

The next phase in the formulation of a process model is to expand the steps of the general outline by incorporating the logic to determine requirements for specific types of operations. The logic is developed based on geometry, dimension, finish, material and special process variations allowed in the part family definition. In the preceding outline, for example, the requirement for deep hole drilling is dependent on the size and length of the thru bore (if one exists). Initial shaping of the part may result in drilling the bore if the size does not require a deep hole operation. Small stepped diameters that can be finish ground in one operation would not be rough turned when shaping the part. Only certain groove features would be turned, others would be crush ground. Diameters are also machined during crush grinding under certain circumstances. Parts made of certain materials may require heat treatment early in the process followed shortly thereafter by a stress relief. Logic would also be included to generate a finish turn operation for part surfaces that can not be finished during shaping operations and do not have tolerance conditions that require grinding.

Logic would be included to machine noncylindrical features (slots, flats, windows) and drill holes if they are specified in the part design. The sequence for installing these features would depend on "timing feature" requirements and the type of feature. Certain features that break into the bore or are of a certain shape may not be installed until later in the process. The preceding outline shows that these features are installed following any requirement for nitriding.

The logic for hardening the part by a nitride process and plating surfaces could depend on several variables. Part material and the type of nitride process specified are key parameters upon which the sequence of operations depends. Only under certain conditions is the entire part nitrided. In situations where specific surfaces are to be nitrided, the process model must provide for masking. The masking process is dependent on the type of part material. Requirements for final plating, such as nickel, would follow the nitride process and the removal of the protecting mask material.

Requirements for finish machining (hone, grind, lap) are dependent on tolerance, surface finish and form conditions and whether nitriding is required. The final operations to be covered by the logic are requirements for inspection, cleaning, marking, preserving and packing. The requirement for electrofilming would also be determined in this part of the model.

Operations Sequence Generated

The end result of incorporating logic into the general process outline for a part family is a process model. The model will generate different sequences of operations conditional on variance in design data. Figure 7 shows an example of an operation sequencing structure that might be found in a process model. Each element or box is the equivalent of a sequence "branching" logic or a test for generating an operation. Boxes from which either of two "paths" can be followed are branching elements of the model. The path followed depends on whether the specific condition is true or false for the part being planned.

For example, boxes 38, 39 and 40 might be elements of the process model to install noncylindrical features and stress relief the part if the material is AMS 5616 and type A nitriding is required. Box 38 would perform a test to determine if the part material is AMS 5616. If the answer is true, the process model would branch to box 39 where another test would be made to determine if the part has a requirement for type A nitride. Again, if the answer is true, the process model would branch to box 40. At this element a test might be made to determine if the part has a timing feature requirement that should be installed before machining the noncylindrical features. If at any of these branch points the answers were false, a different path would be followed. A false answer at element 38, for example, would result in a transfer to box 45. This element would be a test for generating a metalcutting or non-metalcutting operation, such as an OD grind on a centerless grinder or copper plating surfaces. Whether an operation would be generated would depend on the design characteristics of the part being planned.

It can be seen in the example of the operation sequencing structure that there are twelve possible paths. Two of the paths are:

(1) 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 69, 70
(2) 37, 38, 45, 46, 49

This means there are at least twelve sequences of operations that could be generated. There are in fact many more. For example, boxes 37 and 45 are tests for generating operations. Depending on the part design, an operation may or may not be generated in either case. Therefore, in path (2) above, four different operation sequences could be generated. Since both of these boxes occur in all twelve possible paths of the operation sequencing structure, there is a minimum of forty-eight (48) possible sequences of operations. Boxes 41, 42, 43, 44, 47, 48, 49, and 70 are also tests for generating operations. Thus, the number of possible operation sequences gets much larger.

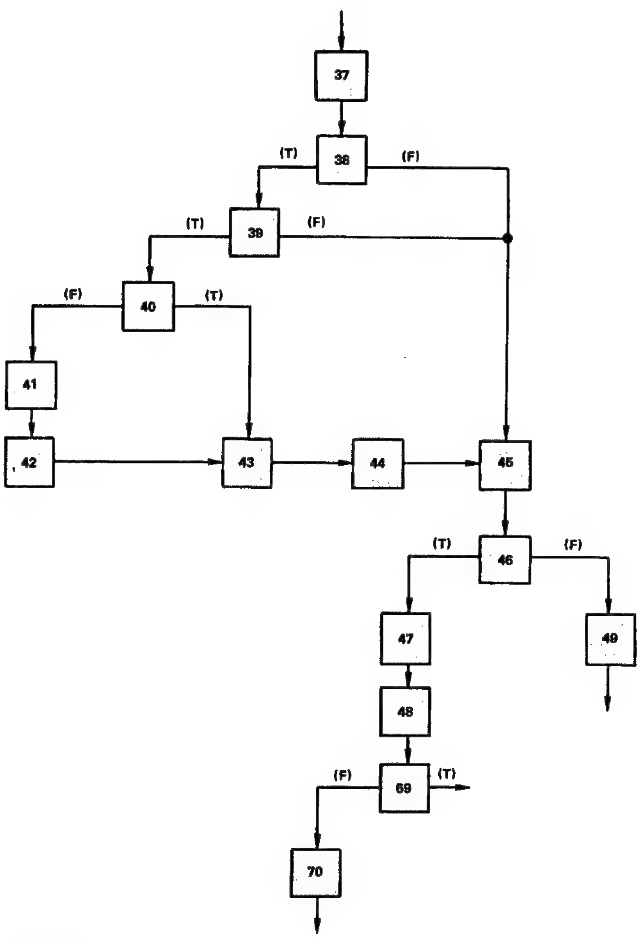


Figure 7

(This article will be concluded in the next issue of the Army ManTech Journal.)

BLAKE L. FERGUSON is a Project Engineer at TRW's Materials Technology Laboratory, where for nearly three years he has worked on the development of new powder metal technology and processes. This has included not only PM forgings, but also PM technology for increasing the utilization of high temperature materials and the minimization or elimination of strategic elements such as chromium and cobalt. For three years while working on mechanical metallurgy of steels for Republic Steels, he gained expertise in the cold formability, workability, and machinability and mechanical testing of steels. He received his B.S. in Metallurgy from Drexel Institute in 1972, after which he earned an M.S. in Metallurgy there in 1974 and a Ph.D. in Metallurgy in 1976. A member of the American Society for Metals and the American Powder Metal Institute, he serves on the Powder Metals Subcommittee of the ASM's Metalworking Committee.

FRANK T. LALLY was Project Engineer on the project described in the accompanying article before he retired in 1979 from the Metallurgy Department of TRW's Materials Technology Laboratory after 39 years service with the firm. He presently works as a consultant for TRW. He performed the initial powder metal work in the 1950's on the development of extrusion and precision forging techniques and the fabrication of porous iron bodies. He also worked on powder fabrication processes for iron, titanium, molybdenum, tungsten, cermets, and ceramic materials.

No Photo Available

Structural Process Variations Demonstrated

50% Savings for P/M Forgings

In a recent demonstration program, TRW successfully used powder metal (P/M) forging to produce three different structural parts with properties comparable to those of conventionally forged and machined parts. Cost projections indicate that P/M forging on a production basis will reduce conventional processing costs by about 50 percent for two of the parts, with substantial savings in both machining time and material. Cost reductions as high as 35 percent were projected for the third part.

In approaching the forging of each of these parts, TRW carefully considered compaction techniques, sintering variables, preform design, and forging variables and their effects on part performance and cost. As a result, process variations were applied and adapted to meet requirements of the individual parts. This approach ensured manufacturing process recommendations that reflect optimum part properties and cost.

Wide Range of Characteristics Checked

The demonstration parts were a machine gun accelerator, differential gears, and a machine gun cover. The machine gun accelerator was forged to demonstrate the feasibility of the process on a small part with a high ratio of surface area to volume. To forge the accelerator, sintered preforms of 4640 steel powder were hot repressed to full density with minimum deformation. The differential gears were forged to represent axisymmetric parts. For these gears, sintered preforms requiring gross metal flow were hot forged to maximize properties and minimize costs. The machine gun cover—representing a complex shape—was isothermally forged from both loose powder and sintered preforms.

P/M forging is considered a promising manufacturing process because it combines the cost saving advantages

of sinter powder technology with the ability of forging to enhance part performance. Although classified as a powder metal process, it actually is a type of precision forging. P/M forged parts develop full density, along with the mechanical properties needed for high performance applications. In TRW's demonstration effort, microstructural uniformity and final oxygen content were carefully controlled and parts were forged to near theoretical density (greater than 99.5 percent). As a result, the P/M forgings were as ductile, tough, and fatigue resistant as conventionally forged bar parts. Because of the inherent precision of P/M forging, much better material utilization and significant reductions in machining time were obtained.

Accelerator A Small, Thin Part

In production, the accelerator for the Army's M-85 .50 caliber machine gun is forged and machined from 4340 steel bar stock. Its manufacture requires six forging steps and twenty seven machining steps. In the demonstration program, TRW produced accelerators by compacting and sintering 4640 steel powder to a preform, hot repressing the preform to full density in one blow, and finish machining the part in just seven steps. Figure 1 shows the preform, the forging, and the finished part.

Repressing (which results in minimum deformation) was utilized because the relatively thin sections and large surface area of the accelerator are not conducive to metal flow during forging. Parts of this type require uniform consolidation in all sections of the preform during forging. In compacting the accelerator preforms, split punch tooling was used so that the amount of powder in each section could be controlled. As a result, the forged density was at least 99.5 percent in all sections.

Figure 1

Wrought Bar Stock Equalled

After compaction, the preforms were sintered at 2200 F for one hour in an atmosphere of dry hydrogen plus one percent methane and then soaked five hours at 2200 F in a reducing atmosphere. The tool steel dies were gas torch heated to 400 F and sprayed with a graphite/water suspension prior to forging. The parts were forged at 80,000 psi in a hydraulic press. Forged parts were finish machined, heat treated, and chrome plated.

As shown in Figure 2, tensile properties of P/M forged 4640 at various hardness levels are comparable to those of wrought 4640. Of equal importance, the room temperature impact strength of 4640 P/M forgings equalled that of 4640 bar stock. Finally, fatigue resistance comparable to that of wrought 4340 steel was demonstrated (Figure 3).

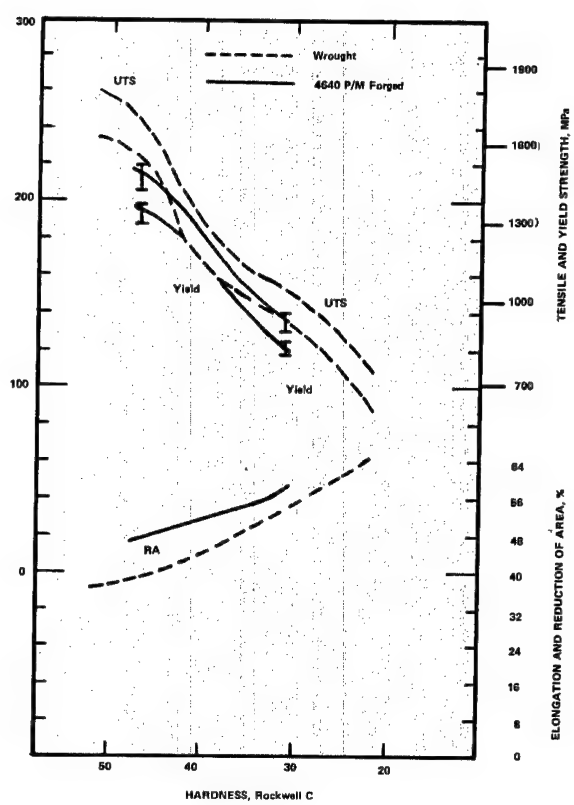


Figure 2

Procurement Authorized

Based on this demonstration effort, TRW projected sizable cost reductions for P/M forgings. Table 1 shows a cost analysis for P/M forged accelerator production. This analysis is based on a 1000 piece lot and a projected

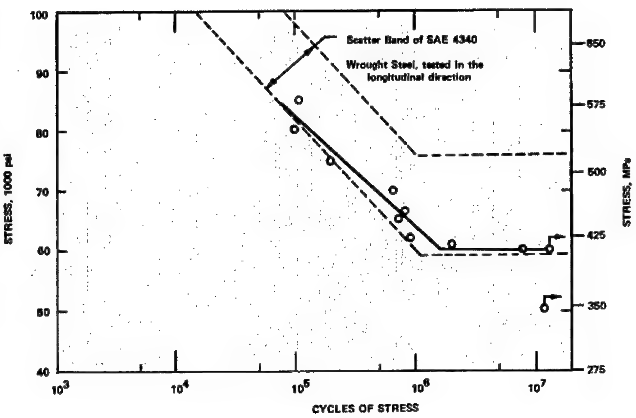


Figure 3

CONVENTIONAL PROCESS				MINIMUM DEFORMATION P/M PROCESS			
OPERATION	STANDARD HRS/PC	$/PC	SETUP HRS	OPERATION	STANDARD HRS/PC	$/PC	SETUP HRS
Heat & Forge	.0670	1.68	3.0	Heat Treat	.0200	0.50	4.0
Trim	.0083	0.21	1.0	Sinter	.0025	0.06	-
Coin	.0083	0.21	1.0	Forge	.0200	0.50	3.0
Heat Treat	.1600	4.00	-	Heat Treat	.0800	2.00	-
Sandblast	.0300	0.75	-	Sandblast	.0300	0.75	-
Machine (27 Steps)	.8012	20.00	60.3	Machine (7 Steps)	.2699	6.75	13.6
Finish	.1882	4.70	1.1	Finish	.1882	4.70	1.1
Material	-	1.50	-	Material	-	0.26	-
Totals	1.2630	33.05	66.4	Totals	.6106	15.52	24.7

Table 1

die life of 50,000 pieces. Most of the approximate 50 percent cost savings results from reduced machining time. The P/M forged accelerator contains about 90 percent of the starting material, while a conventionally forged part uses only 17 percent of the starting bar stock.

TRW delivered 400 of the P/M forged accelerators to the Army for testing. Results of extensive evaluation, including firing tests, were satisfactory and the Army subsequently authorized procurement of P/M forgings for 26 M-85 components.

Gears Typify Axisymmetric Parts

In the second part of this effort, TRW produced a total of 300 differential gears of four types for light duty Army trucks using P/M forging. These included two side gears and two mating pinions, as shown in Figure 4. Use of a simple preform geometry promoted extensive metal flow and ensured complete die filling and full density. The pinions were produced as net forgings that required only finish machining of a chamfer on one end. The side gears were formed by a combination extrude/forge one blow operation. The teeth on these gears were left as forged, but finish machining of a back face, the shaft, and the outer diameter was required. All parts were forged from 4620 steel powder, which subsequently was carburized.

Weight control of the preform was critical, since machining was minimized. Preform density also was critical, with densities below 83 percent resulting in cracking of tooth tips during forging. Proper die filling for good tooth forming was controlled by the preform shape.

Preform sintering conditions were the same as those used for the machine gun accelerators. The side gear was forged at 50,000 psi and the pinion at 80,000 psi, both on a hydraulic press.

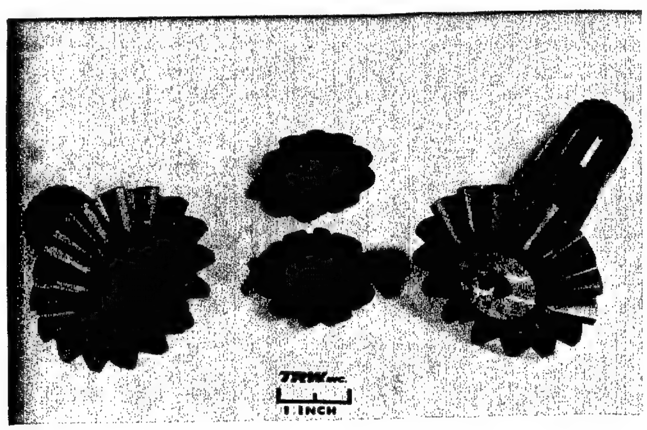


Figure 4

Large Quantities Multiply Savings

The Army's evaluation of these gears included field trials in which gear sets were mounted in seven M151A2 1/4 ton trucks. Four sets were removed and inspected after 10-12,000 miles of service and three sets after 20-22,000 miles. Based on test results, the Army judged the gears suitable for vehicle applications.

P/M processing of these gears offers both reduced machining costs and more efficient material utilization. Small gears such as the pinion typically are machined from bar stock with only about 30 percent material utilization. The side gears represented larger parts, which normally are

machined from forged blanks with material utilization of 50 percent or less. P/M forging of both types of gears used 90 percent or more of the starting material, so very significant material cost savings are possible for large quantity items in addition to the labor savings from reduced machining time. Based on production of 200,000 units a year, projected cost savings for P/M forging are 23 percent for the side gear and 25 percent for the pinion.

Gun Cover A Complex Shape

Finally, TRW adapted P/M forging to the M-85 machine gun cover shown in Figure 5. Because of the complexity of this part, however, a different approach was required. The large plan area (35 sq. in.), the tall, thin ribs, and the multilevel nature of the cover made it necessary to combine P/M forging with isothermal forging. In isothermal forging, the dies are heated to the same temperature as the preform to minimize die chill, permitting slow deformation rates. In this study, isothermal forging of both preforms and loose powder was investigated using 4630 steel.

A preliminary investigation established process parameters for this material. Based on these results, preforms were compacted to 80-85 percent density by cold isostatic pressing at 30,000 psi. The preforms were sintered at 1450 F for 18 hours in a hydrogen plus methane atmosphere and both the preforms and die were preheated to 1600 F. Prior to heating, the preform was coated with boron nitride, boric acid, and graphite for lubrication. The parts were forged at 20,000 psi for 15 minutes. After forging, they were homogenized at 2200 F for 2 hours.

In the loose powder approach, cold powder was charged into the hot die (1600 F) and the die was closed. An initial pressure of 6000 psi was applied for 15 minutes while the powder warmed to the die temperature. The forging pressure of 20,000 psi then was applied for another 15 minutes.

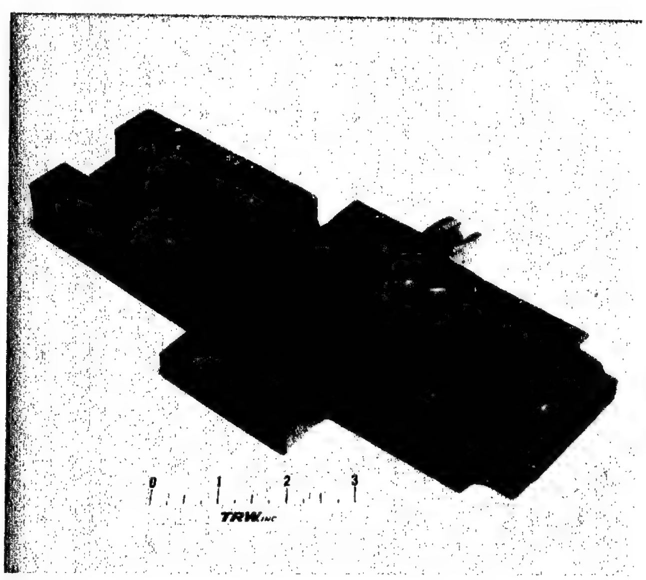


Figure 5

Further Study Offers Promise

The forged parts were metallographically examined and found to be fully dense. However, carbon and oxygen control were erratic. Before the process is ready for production, further investigation is needed to identify high temperature coatings that will provide an oxidation barrier and adequate lubrication, while eliminating die wall buildup.

If the process can be established on a production scale, its precision should lead to cost reductions exceeding 50 percent. Figure 6 compares costs for the isothermal hot die P/M forging process described here with those for conventional forging and machining. Again, greatest savings result from the reduced machining time. With proper modification, the process appears very promising for manufacturing net or near net forgings with a large plan area.

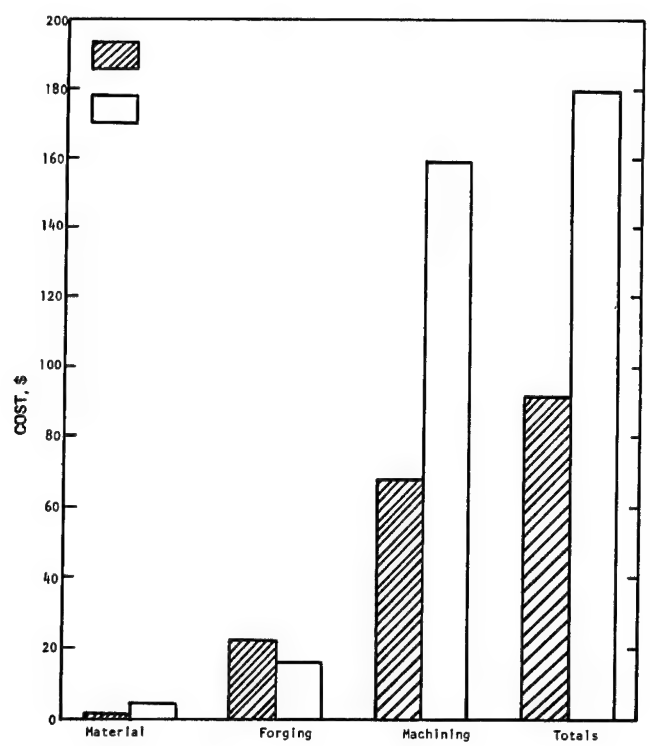
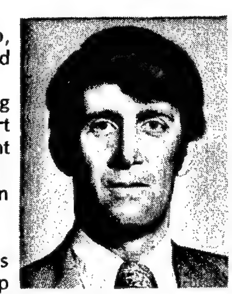


Figure 6

Boon to Turbine Engine Design

HIP of Rene' 95

MARVIN B. HAPP is a Senior Process Engineer, Manufacturing Technology Operation, Aircraft Engine Group, of the General Electric Company, Lynn, Mass., where he has been active in the application of PM near net shape technology to small aircraft engine components. Mr. Happ first joined G.E. in 1952 after receiving his B.S. in Metallurgical Engineering from Rensselaer Polytechnic Institute, later leaving the company to earn his M.S. in Metallurgy from M.I.T. in 1956. He then was employed as Chief Metallurgist for the Walworth Company, Chief Metallurgist and Assistant General Manager of Tang Industries, Inc., and as Senior Metallurgist for the Raytheon Company. After six years' association with the Metallurgical Materials Division of Texas Instruments, Inc., first as Engineering Supervisor of precious metal cladding and later as Senior Technical Advisor and Project Manager for clad metal systems in electronics, he rejoined G.E. in 1972. He since has successfully completed programs in net shape isothermal forging and activated diffusion bonding of a titanium bellcrank for the F101 engine afterburner actuation system. Mr. Happ holds five metallurgical patents. He is a member of Tau Beta Pi, Phi Lambda Upsilon, and Sigma Xi, and is active in the AWS, ASM, and APMI, and is a Registered Professional Engineer in Massachusetts.



PAUL SAN CLEMENTE is Manager, Manufacturing Engineering, Aircraft Engine Group, General Electric Co., Lynn, Mass. He joined G.E. in 1965 and since has worked closely with the manufacturing segment as a welding engineer, later as Manager of Shop Support and Joining Development. His next assignment was as Manager of Raw Materials Quality Control for the Aircraft Engine Group, then in 1976 he was chosen to head up the Lynn Aircraft Engine Group's Powder Metal Group. During the past three and one half years he has worked actively inhouse with vendors to develop and promote technology for making near net shape powder metal components for new engine programs. Prior to joining G.E., he worked for United Nuclear Corp. as a welding engineer and for the Sippian Corp. as Chief Metallurgist. He received his B.S. in Metallurgical Engineering from Rensselaer Institute in 1957. He is a member of the American Society of Metals and holds several patent disclosures related to metallurgical processes.

Rene' 95, an important superalloy for high performance turbine engine applications, becomes even more useful when it is fabricated by hot isostatic pressing (HIP). Benefits of the process are shown on General Electric's T700 aircraft engine, which has hot isostatically pressed turbine disks and cooling plates. The engine is now in its third year of production for use on the Army's Blackhawk helicopter.

Compared with forging, HIP conserves material, allows more complex shapes to be formed, and reduces the amount of machining required. Raw material savings of up to 50 percent are possible—a vital factor in light of the scarce, expensive alloying elements used in Rene' 95.

Wider Use Under Way

Because of these benefits, applications of the process are proliferating. Rene' 95 parts manufactured by HIP are now used extensively on two larger engines, with the same advantages that are realized on the T700. Major activity is also under way to introduce HIP products to other engine lines through application of near net shape technology.

GE's HIP development work was done under an Army contract and was directed by the U. S. Army Mobility Research and Development Laboratory. Processing work was done by Colt Crucible Materials Research Center and Carpenter Technology Corporation Research and Development Center. Both companies now are sources for HIP Rene' 95 hardware.

Shortcomings Overcome

Rene' 95 is a nickel base superalloy (composition given in Table 1) developed by GE for high temperature, high strength applications. When it was introduced during early stages of T700 turbine engine development, several inherent problems became evident. First, the alloy uses high percentages of scarce alloying elements. Second, it is difficult and expensive to forge and does not lend itself to close contour forging. This meant more material

• CARBON	0.04 - 0.09	• ZIRCONIUM	0.03 - 0.07
• MANGANESE	0.15 Max.	• TITANIUM	2.30 - 2.70
• SILICON	0.20 Max.	• ALUMINUM	3.30 - 3.70
• SULFUR	0.015 Max.	• BORON	0.006 - 0.015
• PHOSPHORUS	0.015 Max.	• TUNGSTEN	3.30 - 3.70
• CHROMIUM	12.00 - 14.00	• OXYGEN	0.015 Max.
• COBALT	7.00 - 9.00	• NITROGEN	0.005 Max.
• IRON	0.50 Max.	• HYDROGEN	0.001 Max.
• TANTALUM	0.20 Max.	• NICKEL	Remainder
• COLUMBIUM	3.30 - 3.70		

Table 1

was required to produce parts. Finally, and compounding these problems, Rene' 95 is very difficult to machine. Thus, at the Army's request, GE began to investigate powder metallurgy technology. Initial studies indicated that use of the HIP process could reduce the material starting weight by 35 percent compared with the conventional forging method. With that positive indication, HIP became part of the T700 development. When the Blackhawk made its maiden flight in November 1978, it was powered by two T700 engines (Figure 1), with HIP Rene' 95 disks and cooling plates.

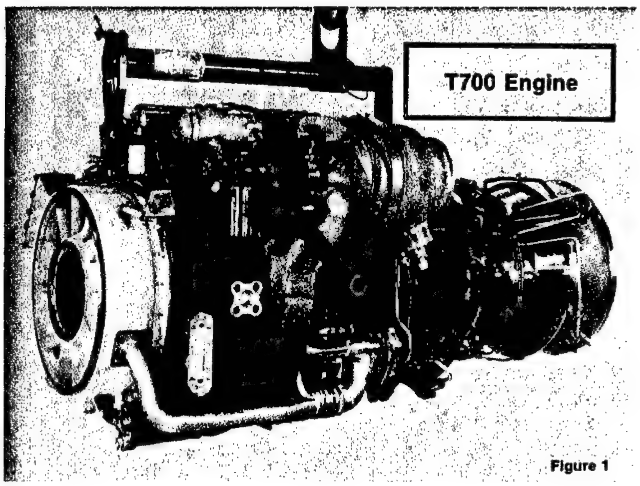


Figure 1

Process Description

To start the hot isostatic pressing process, a prescreened powder of the proper chemical composition is loaded into a clean, evacuated container. The container is sealed and placed in a furnace or autoclave. When high pressure is applied at elevated temperature, the heated container collapses, compacting the metal powder. The temperature is high enough so that the powder particles become plastic and coalesce to form a solid alloy. There are several key steps in the process, including those that precede the actual pressing.

Atomization is the powder forming process. The alloy is melted in a nonreactive crucible and then poured into the reservoir of an atomizing nozzle, all under vacuum. As the liquid metal leaves the nozzle, a high velocity argon gas stream impinges on it. The argon breaks the liquid into small droplets, which solidify to powder form as they fall into a collection chamber. The process is illustrated in Figure 2.

Screening removes oversize and nonspherical particles that would interfere with packing uniformity during hot isostatic pressing. The chemistry and residual gas content of the powder are also checked at this time.

During **blending** the powder from several atomization runs is mechanically mixed to insure full homogeneity of particle size.

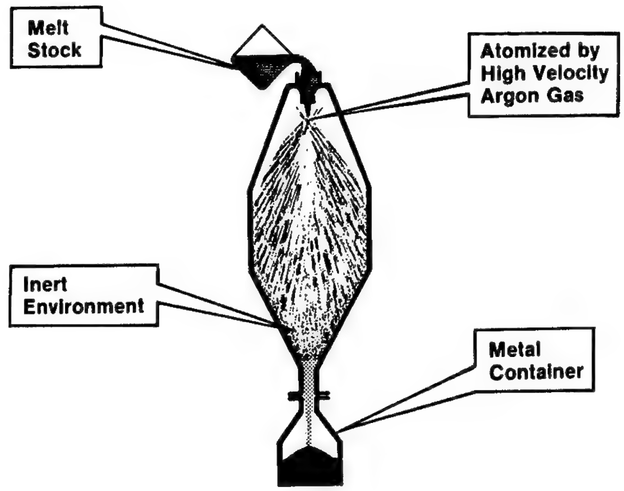


Figure 2

Container fabrication involves shaping container components from low carbon or stainless steel sheet to closely resemble the final product. The preshaped components can be hydroformed, spun, or die formed and are generally joined by gas tungsten arc welding.

In a **filling and sealing** operation, the container is filled with powder by gravity flow through a tubular stem. After filling, which may be assisted by vibrating the container, the fill stem is crimped off and welded shut under vacuum.

Compaction occurs when the sealed container is heated and pressed in an autoclave and the individual powder particles coalesce to form a solid approaching theoretical density. Typical compaction parameters for Rene' 95 are 15,000 psi and 2050 F for a minimum of two hours.

The **heat treating** cycle to achieve full mechanical properties in HIP Rene' 95 is:

- Solution treat at 45 F below the gamma prime solvus temperature
- Quench
- Age at 1600 F for one hour and air cool
- Age at 1200 F for 24 hours and air cool.

After heat treatment, the container is removed either by machining or chemical processing and the part is ultrasonically inspected for internal integrity and examined by a fluorescent penetrant technique for surface flaws. A part that qualifies under these tests is ready for finish processing.

Pressing of T700 Parts

Several years were spent on developing the basic HIP process for production of T700 disks and cooling plates. To begin, various canning techniques were examined, considering the two parts separately. These studies indicated

that individual containers for each part provide the most economical production of disks. This is because the disks are thick at the bore—2.4 in., thin at the rim—1.3 in., and have a small internal diameter—1.2 in. The outside diameter of the disk in its ultrasonic testing shape is 6.3 in. On the other hand, the cooling plates are relatively thin—0.7 to 1.3 in.—and have an inner diameter of 2.7 in. and outer diameter of 6.3 in. These plates are produced from long hollow cylindrical HIP logs that are cut to the proper thickness as donuts for heat treatment. Figures 3 and 4 show both ultrasonic shapes and finish machined disks and cooling plates.

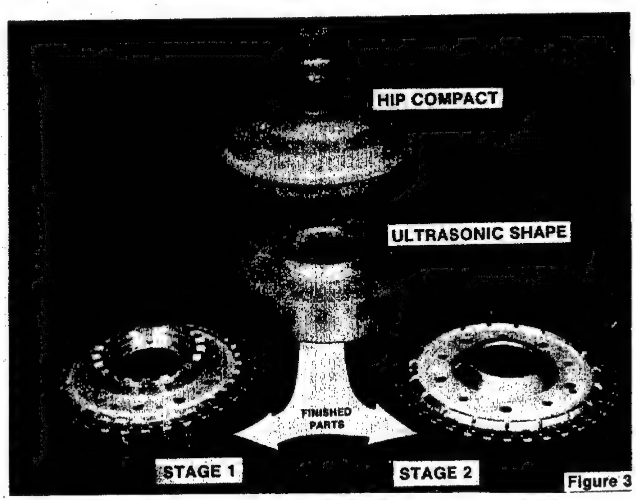


Figure 3

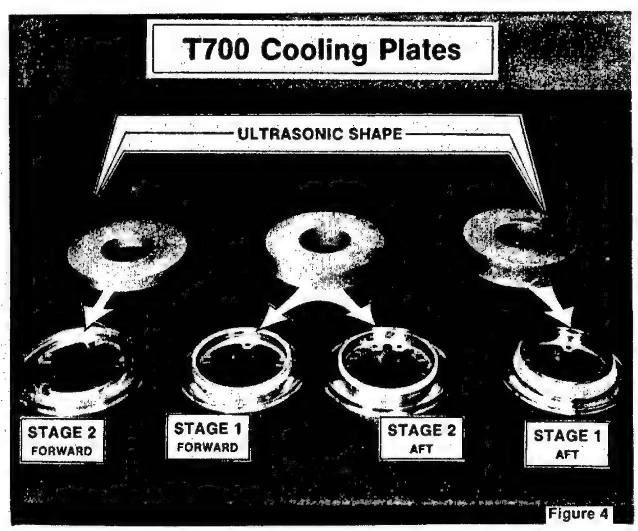


Figure 4

The mechanical properties of the Rene' 95 in these parts more than meet design criteria, as shown in Table 2. Mechanical properties of Rene' 95 are influenced by cooling rate from the solutioning temperature, so heat treatment of the different shapes has to be carefully balanced. If Rene' 95 is quenched too rapidly, it will crack. If quenched too slowly, it will not attain the desired property level. The problem was solved with a salt bath solution and quench that produced consistent results from lot to lot for a given shape.

	Typical	Minimum T700 Requirements
• ROOM TEMPERATURE TENSILE:		
• ULTIMATE STRENGTH	238 ksi	225 ksi
• 0.2% YIELD STRENGTH:	180 ksi	163 ksi
• ELONGATION	16%	10%
• R/A:	18%	12%
• ELEVATED TEMPERATURE TENSILE: (1200°F)		
• ULTIMATE STRENGTH:	218 ksi	203 ksi
• 0.2% YIELD STRENGTH:	165 ksi	153 ksi
• ELONGATION	14%	8%
• R/A:	16%	10%
• STRESS RUPTURE LIFE: 1200° F, 150 ksi	50 Hrs	25 Hrs

Table 2

Adapted to Other Engines

With the process well proven, Rene' 95 forgings in two other production engines have now been replaced with HIP processed parts. The F404 engine for the Navy's F-18 fighter has seven high and low pressure turbine parts and five high pressure compressor spool parts hot isostatically pressed from Rene' 95. There are 14 such parts in the turbine and compressor of the CFM 56, a commercial engine in the 24,000 lb thrust class.

Both of these engines are much larger than the T700, so material savings are greater. The weight of some parts is reduced by more than 50 percent compared with forgings, which can cut material costs in half. The total starting weight for Rene' 95 parts is about 20 times greater on the CFM 56 than on the T700 and about 12 times greater on the F404. Consequently, these new applications can have a significant effect on the powder metal industry.

Development Effort Continues

Advanced engines are now being designed with HIP in mind. A major advantage of the process in these applications is its suitability for fabricating more sophisticated, higher temperature, less workable alloys.

Continued development work with HIP compaction should provide even further improvements in material utilization. For example, process improvements involving material utilization for the T700 are still being investigated despite the maturity of this engine. One program involves heat treating the cooling plate log as an integral unit rather than heat treating the premachined, donut shaped cooling plates as individual pieces. This will allow ultrasonic inspection of the log after heat treatment instead of individual piece inspection and could mean considerable savings in raw material, machining time, and inspection costs.

An interesting weight reduction concept for the F404 engine is also being explored. Figure 5 shows the stage 7 disk and aft shaft for the high pressure compressor spool. They are made as separate parts with a total weight of 226 pounds. Combined into a single shape, as shown in Figure 6, the weight is reduced to 176 pounds and one test ring is eliminated. Furthermore, an inertia welding step required to join the two parts is eliminated. The new design illustrates the shape complexity that is possible with HIP, but not with forging, of Rene' 95 parts.

As experience is gained in controlling dimensions of HIP shapes, less material protection will be needed for the ultrasonic testing of components. The application of dimensional restraint in container design and the advent of new ultrasonic inspection methods could reduce the powder input on larger engines, such as the F404, by at least another 15 percent. Such continuing improvements should lead ultimately to the development of a true near net shape for HIP processed components.

Some Additional Benefits

Some obvious advantages of HIP processing of Rene' 95, such as low input weight, conservation of critical alloying elements, shape flexibility, and reduced machining, have already been discussed. In addition, there are some important side benefits. The most significant are:

- **A More Uniform Product.** There is no macroscopic chemical segregation to adversely influence mechanical properties.
- **Better Ultrasonic Penetration.** HIP enhances the ability of ultrasonic waves to penetrate the material with low background noise, presumably because of a finer, more uniform grain structure.
- **Improved Machinability.** Metal removal rates are higher and there is less tool wear.
- **Shorter Manufacturing Cycle.** Because HIP involves fewer manufacturing steps, a much shorter raw material delivery cycle is possible.

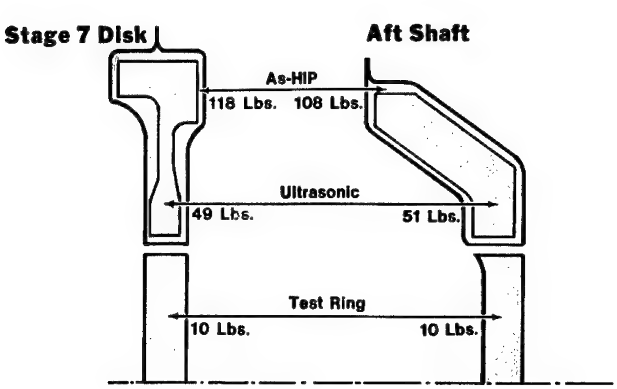


Figure 5

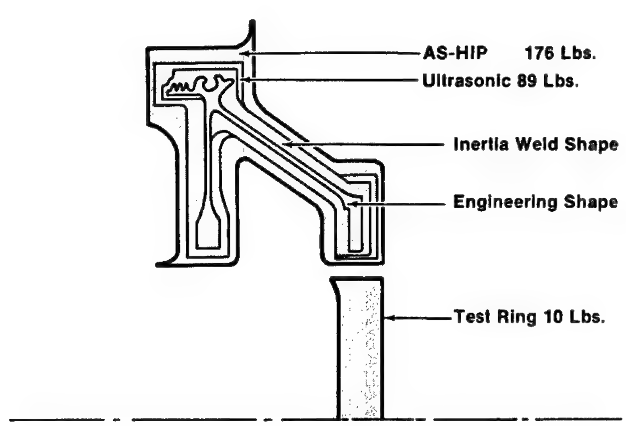


Figure 6

Exothermic Pack Aids DS Casting

Commercial Production Feasible

G. L. VONNEGUT is Section Chief, Foundry Technology, Materials Research and Engineering, Engineering Operations, Detroit Diesel Allison. He has overall responsibility for operation of the DDA Foundry Laboratory and for the planning, organization, coordination, and execution of Materials Laboratories activities required to ensure technical excellence of cast metal components in DDA products. Foundry Technology activities include technical support of and coordination with foundry suppliers and various DDA departments including Procurement, Manufacturing, Quality Assurance, Design and Production Engineering. He recently served as program manager for work performed under AFML contract "Automated Directional Solidification of Superalloys". From 1955 to 1964, Mr. Vonnegut was Supervisor, Product Materials Research. In this capacity, he was responsible for programs related to the fundamental properties, fabrication, and service behavior of a wide variety of ferrous and nonferrous materials, including ultrahigh strength steels, titanium alloys, nickel, and cobalt base high temperature alloys and beryllium for turbine and rocket engine application. From 1953 to 1955, Mr. Vonnegut served as an experimental metallurgist in the Metallurgical Development Section of the Materials Production Laboratory. In this position, he was largely concerned with the development and application of materials and processes for turbine engine components. His professional affiliations include American Society for Metals; Member, ASM Handbook Committee for Hand and Power Spinning; and Consultant, ASM Handbook Committee for Investment Castings. He received a B.S. in Metallurgical Engineering from Purdue University.

No Photo Available

MEHMET DONER is Research Staff Engineer, Materials Research and Engineering, Engineering Operations, Detriot Diesel Allison. Since joining Allison in 1974, Dr. Doner has been responsible for overseeing research and Development efforts in characterization and modeling of materials behavior in support of advanced low cycle fatigue (LCF) life prediction methods applicable to gas turbine engine components. These efforts include the investigation of both LCF crack initiation and crack propagation in gas turbine materials under testing conditions compatible with the engine operating environment. Currently, he is also involved with the application of the exothermic pack D.S. process to the production of SC advanced air cooled turbine blades. From 1970 to 1974 he was employed at the University of Kentucky as a Research Associate. During that period he conducted research in the areas of metal deformation processing, strengthening mechanisms in unalloyed titanium and commercial titanium alloys and plastic deformation of metals under multiaxial stress states. Prior to his employment at the University of Kentucky, he was a postdoctoral fellow for a year at the University of Pittsburgh, where he conducted research on low cycle fatigue behavior of unidirectionally solidified eutectics. He received B.S. and PhD. degrees in Metallurgical Engineering from Pittsburgh University and has been a NATO Fellow and Visiting Scientist, Comision Nacional de Energia Atomica, Buenos Aires, Argentina. His Ph.D. dissertation involved the identification of LCF crack initiation mechanisms in columbium single crystals. He is a member of the American Society of Metals and is a member, National Materials Advisory Board Committee on Fatigue Crack Initiation at Elevated Temperatures.

No Photo Available

Ceramic molds for directionally solidified (DS) castings are being effectively preheated by an exothermic pack process developed at Detroit Diesel Allison (DDA) Division of General Motors. With its cost advantages proven on a pilot plant scale, the technology now has been transferred to two commercial foundries and developed on a production basis. This work at Jetshapes, Inc., and TRW, Inc., has shown that the directional solidification process using an exothermic pack can produce well oriented, high quality castings of simple configurations and of small, cored turbine blades. Both foundries also have demonstrated capability to produce single crystal castings of an advanced aircooled turbine blade design. The pack process is most suitable for castings with no larger than 6 or 7 inches in size and offers cost savings for a broad range of small airfoils. Manufacturing technology development has been under U. S. Air Force sponsorship.

No Nickel, Cobalt Reactivity

The basic process was developed at DDA and refined sufficiently to ensure its ultimate adaptation for commercial scale automated production. The "standard practice" outlined by DDA was modified as necessary at Jetshapes and TRW to suit the specific production equipment, mold practice, and exothermic material used. A key in the DDA effort was development of a shell molding system using a highly refractory Colal P-Alumina prime coat. This system met the need for an easily fabricated, reasonably priced ceramic shell mold. A key system advantage is that it does not react with nickel and cobalt base alloys during the exothermic reaction process, which involves high temperatures for extended time. This development, alone, paved the way for dramatically improved casting quality and reduced costs.

Simplifies Preheating

Directional solidification requires extremely high mold preheat temperatures (2900-3100 F). In conventional DS practice, this temperature is attained using auxiliary heating apparatus or moving heat sources such as induction coils. Using exothermic material, the mold is externally preheated by a uniform temperature pack so that no appreciable gradient exists in the mold before pouring. After pouring, heat is extracted rapidly by a chill plate, producing the temperature gradient in the melt necessary for directional solidification.

No specialized furnace equipment is needed—only the addition of a chill plate to conventional melting and pouring equipment. Thus, the high facility setup costs of induction coil/susceptor methods are avoided. Of equal importance, all producers of conventionally cast airfoils can quickly adapt their facilities to the process. Some of the blades successfully cast during pilot plant development are shown in Figure 1.

Heat Transfer Rapid

Basic steps in the preheating, casting, and cooldown cycle for the DDA directional solidification method are shown in Figure 2. The mold is placed in a preformed insulating sleeve and exothermic material is added to form a pack. The exothermic material is ignited and allowed to burn until the exothermic reaction is complete. Pack temperature is monitored, and when the mold and surrounding pack have reached the desired preheat temperature, they are moved as a unit and placed on a copper chill plate inside a conventional vacuum furnace for pouring. Pouring is done conventionally after evacuation of the furnace chamber. Heat is transferred rapidly from the bottom of the castings by the chill plate to achieve directional solidification. The mold, still in its exothermic pack, then is removed from the furnace and transferred to a secondary cooling location.

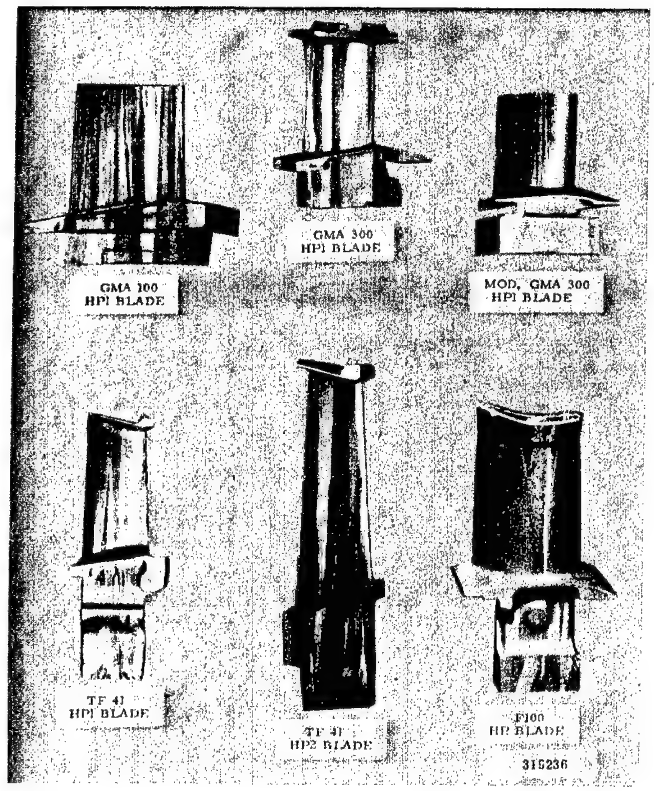


Figure 1

Adaptation for Production

At Jetshapes, the equipment needed to duplicate this process as closely as possible has been installed. The mold pack is the same size and shape, and the same type of ceramic insulating sleeve is used. All molds are poured using a vacuum furnace equipped with an interlock system, which enables meltdown to proceed during evacuation of the mold assembly in a separate chamber. Except for a watercooled chill plate measuring about 16 square inches, conventional investment casting equipment is used.

Shell molds are prepared conventionally using wax patterns on a baseplate. After molding and dewaxing, the fired shell mold is placed in a stainless steel tray. A ceramic fiber sleeve container for the exothermic material is placed around the mold and filled with exothermic nuggets. To ignite the exothermic material, the assembly is placed in an oven at a temperature of 2000 F; ignition takes 4 to 6 minutes. Mold temperature then is controlled by the length of the burn cycle. When the predetermined cycle is complete, the mold is removed from the oven and covered with insulation to minimize heat loss while the exothermic reaction is completed. The mold then is positioned on the chill plate for casting. After pouring, the solidification dwell period ranges from 5 minutes for short castings to 30 minutes for castings of 6 to 7 inch dimensions. The casting is allowed to cool outside the furnace before it is knocked out of the mold and processed conventionally.

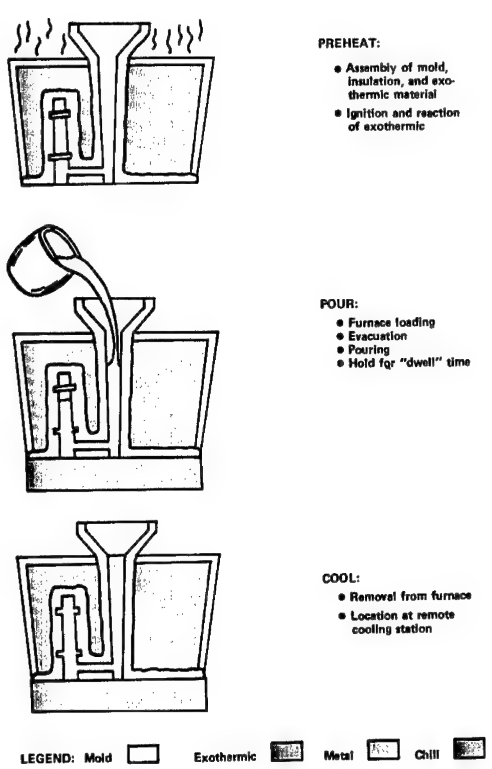


Figure 2

TRW Process Differs

TRW already had facilities for an exothermic technique for directional solidification. These have been adapted to the DDA method. Significant variations in the TRW processing sequence are as follows:

- There is no interlock system in the pouring furnace.
- Larger furnace equipment allows larger molds to be used.
- Different mold materials are used.
- Preformed pack insulation is not used for mold heat retention.

At TRW the molds are placed on a flat, smooth refractory block and surrounded by a tapered mild steel can, lined with a single layer of alumina fiber felt. The can is wider at the top. Exothermic briquettes are placed in the can and a heavy refractory blanket is positioned around the inside top of the can to slow cooling and encourage the formation of a thermal gradient. The can is then placed in an oven at 1800 F for 5 minutes to remove residual moisture and preheat the briquettes for easy ignition. A multiple head oxyacetylene torch is used to ignite the pack after removal from the preheat furnace. This method improves the uniformity of ignition and of subsequent pack burning. After ignition, which takes about one minute, the reaction spreads over the entire surface of the pack. A double layer of insulating blankets minimizes heat loss from the top of the pack during the reaction, which lasts 10 to 15 minutes. When the reaction is complete, the mold and pack are placed on the water-cooled chill plate in the pouring furnace for casting. (The can is placed immediately in front of the furnace for ignition to decrease transfer time.) Furnace cycle time is 15 minutes, including 5 minutes' dwell time on the chill plate after pouring. After cooling outside the furnace, castings are removed by a simple hammer knockout operation and processed as conventional DS castings.

Quality Good

Both foundries have produced turbine blade castings of acceptable quality, as determined by nondestructive testing. Consistently good grain orientation has been obtained. In general, parts up to two inches long can be cast at the rate of two molds per hour per furnace. Longer blades require correspondingly longer furnace cycles—up to one hour per mold. These times can be reduced if acceptable methods for better furnace utilization—that is, preheating molds during furnace cool of the prior mold—are devised. The problem is that adequate cooling during the in-furnace chill appears to be critical to prevent grain boundary cracking. More effective utilization of furnace time is possible if equipment can be designed that will permit removal of the mold and chill plate as a unit immediately after pouring.

Single Crystal Castings Made

Jetshapes and TRW both have also undertaken a limited program to demonstrate the feasibility of using the exothermic pack process to produce single crystal castings of an advanced aircooled turbine blade. Mar-M247 alloy was used to cast three molds in each foundry, using the processes just described. At TRW, the blades were cast root up, using helical crystal starters. Casting at Jetshapes was done root down, using right angle crystal selectors. Typical single crystal airfoil castings produced are shown in Figures 3 and 4. The program results have shown that the exothermic pack process can produce well oriented cored turbine blade castings in which at least the airfoil is a single crystal. The stacking axis orientation of a large percentage of the castings produced appeared to be within acceptable limits.

Root Orientation Affects Product Quality

In the TRW castings (cast root up), secondary grains nucleated in the platform and the root areas. This did not occur in the Jetshape castings (cast root down), which were all complete single crystals. On the other hand, nondestructive inspection indicated that most of the TRW castings were of high quality, while most of the Jetshapes castings showed microshrinkage porosity on the top surface of the platform or in the fillet from the airfoil to the platform.

Although further development work is needed, the Detroit Diesel Allison Division of General Motors has concluded that the exothermic pack process can produce well oriented single crystal castings in small turbine blade configurations on a commercial production scale.

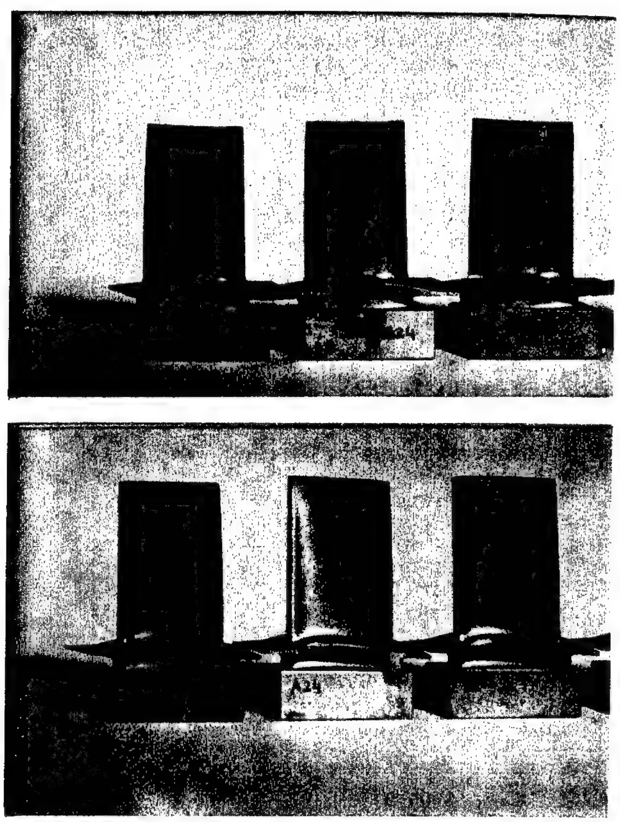


Figure 3

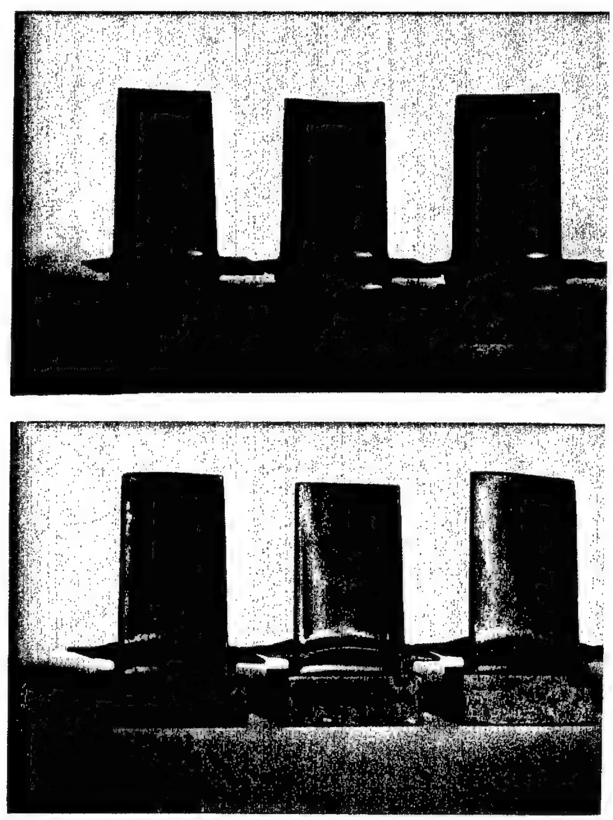
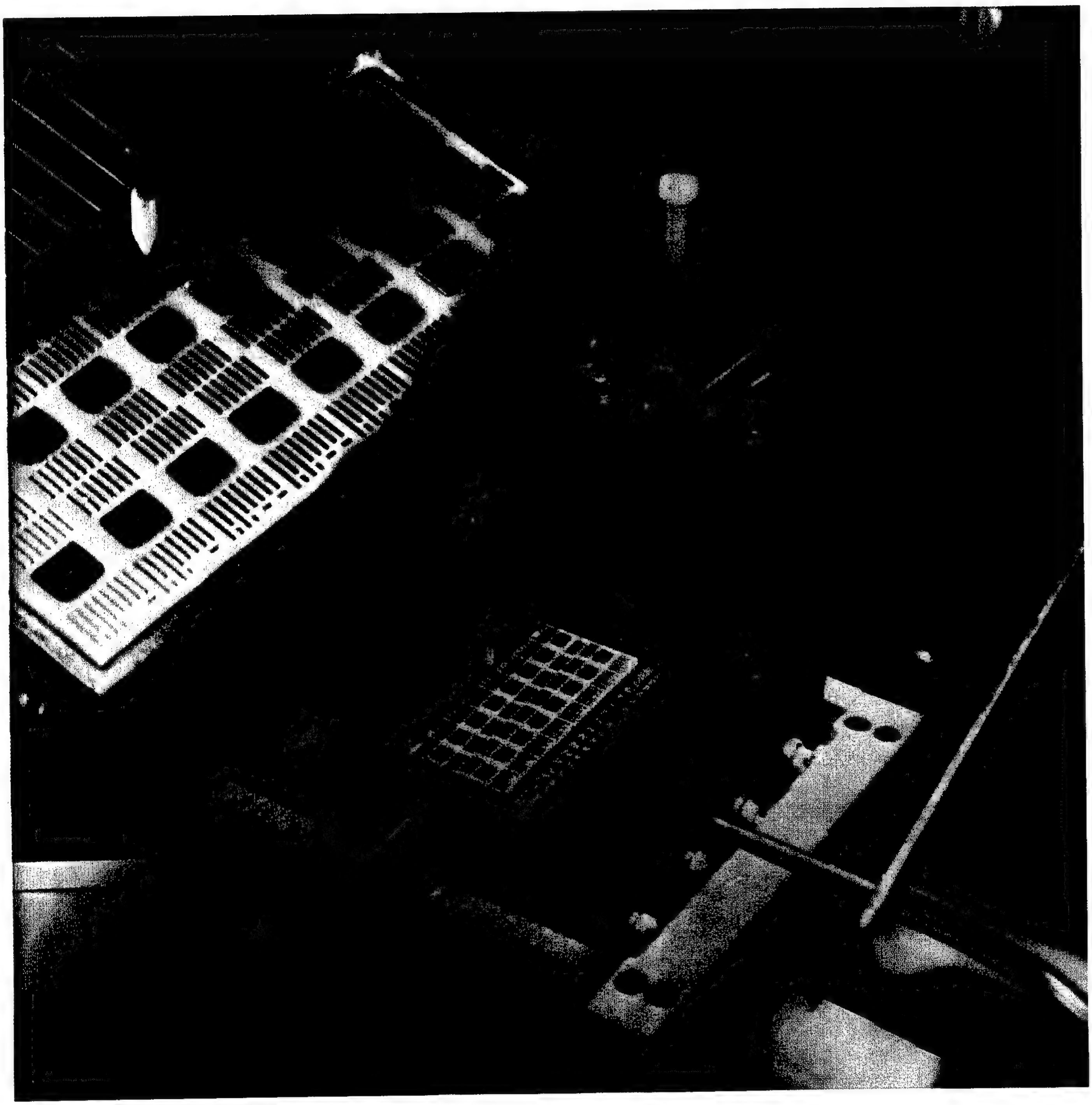


Figure 4

US Army
ManTech Journal

Reaping the MT Program Benefits

Volume 5/Number 1/1980



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US Army ManTech Journal

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ABOUT THE COVER:

The automated fabrication of MNOS BORAM (metal nitride oxide semiconductor block oriented random access memory) chips roughly the width of a 25 cent coin is seen in these two photographs. The larger view illustrates the computer controlled machine that performs precision soldering of contacts as shown in the inset photo. Developed by Westinghouse, the MNOS BORAM devices are being used in the Blackhawk helicopter's Accident Information Retrieval System and in the Marine Integrated Fire and Air Support System. A complete discussion of the development of these devices is given in this issue of the U.S. Army ManTech Journal (Part II of the article) and in previous Volume 4, Number 4, of the magazine (Part I of the article).

Comments by the Editor

The U. S. Army ManTech Journal reached a new milestone in its youthful history when its Editor-in-Chief, Dr. John J. Burke, retired from Government service August 31 of this year. Dr. Burke was the driving force behind the initial concept of the ManTech Journal, and established the magazine's format and character. He clearly visualized the need for such a publication and defined its objectives—to accelerate exchange of information about new manufacturing technology through reports on manufacturing and management techniques newly implemented by the Army. Dr. Burke culminates his remarkable career that spanned over 30 years of Government service, retiring as Associate Director for Plans and Programs at the U. S. Army Materials and Mechanics Research Center, Watertown, Massachusetts.

Over the past 24 years at AMMRC, he has served in a wide variety of positions. In addition to his extensive technical experience in research and engineering, he was noted for his expertise in technical forecasting and long range planning.

Immediately prior to his appointment as Associate Director, Dr. Burke was Planning Director, and prior to this he was Chief of the Processing Research Division, directing a variety of efforts designed to improve the processing of metals, ceramics, polymers, and composites. Dr. Burke is the inventor of the SPIDERCHART (Systematic Planning for the Integration and Direction of Engineering and Research) management concept and has been guest lecturer on that concept at many academic and industrial organizations.

A member of American Men of Science and Sigma XI and numerous other scientific groups, Dr. Burke holds a B.S. Degree in Physics and an M.S. in Geophysics from Boston College, and an Engineering Degree, an M.S. in Metallurgy, and a Sc.D. in Metallurgy and Materials Sciences from M.I.T.

He authored numerous Government reports and was coauthor of the first book on titanium, "Titanium in Industry". In addition, he is coeditor of about twenty technical books. Dr. Burke will continue to be active in his new role of industrial consultant.

The ManTech Journal was honored to be asked to provide a special issue devoted to the recently completed MTAG 1980 meeting held in Miami Beach. Several new topics were presented at this meeting, notably, the mini seminars on foreign manufacturing technology and academia activities in MT. Several of these papers will appear in

RAYMOND L. FARROW, Editor of the U. S. Army ManTech Journal, is Chief, Technology Planning and Management Division, Army Materials and Mechanics Research Center, Watertown, Massachusetts. He has served in a variety of technical and executive managerial positions for over twenty-four years at AMMRC. In addition to his technical experience in the areas of high temperature materials, thermal radiation and laser effects on materials, Mr. Farrow is noted for his broad experience in research management. Prior to his present appointment, he served as Staff Advisor to the Director and prior to this was responsible for the development of research programs and for the coordination of technical follow-on efforts. In his current position, Mr. Farrow is responsible for coordinating programs for the centralized management of the Army's manufacturing technology efforts—including direction of technical and economic assessments and supervision of management information system developments, as well as initiation of technology transfer activities and the coordination and management of the Center's Research and Development Program. He has worked extensively on the development of the SPIDERCHART management concept and has been a guest lecturer at Boston University, Georgia Institute of Technology, Tufts University, Northeastern University, and the University of Connecticut as well as industrial and governmental organizations. Mr. Farrow has served as a consultant to Government and Industry in the areas of R & D management and economic planning, is a patent holder, and the author of both technical and managerial articles. He is a member of Beta Gamma Sigma, North American Society for Corporate Planning, and the American Defense Preparedness Association. He was a Sloan Fellow at Stanford University, holds an M.B.A. with Honors in Management from Boston University, an A.B. in Physics from Clark University, and has done graduate studies in Mathematics at Worcester Polytechnic Institute and Northeastern University.

early issues of the Army ManTech Journal in the form of in-depth articles which should provide high reader interest.

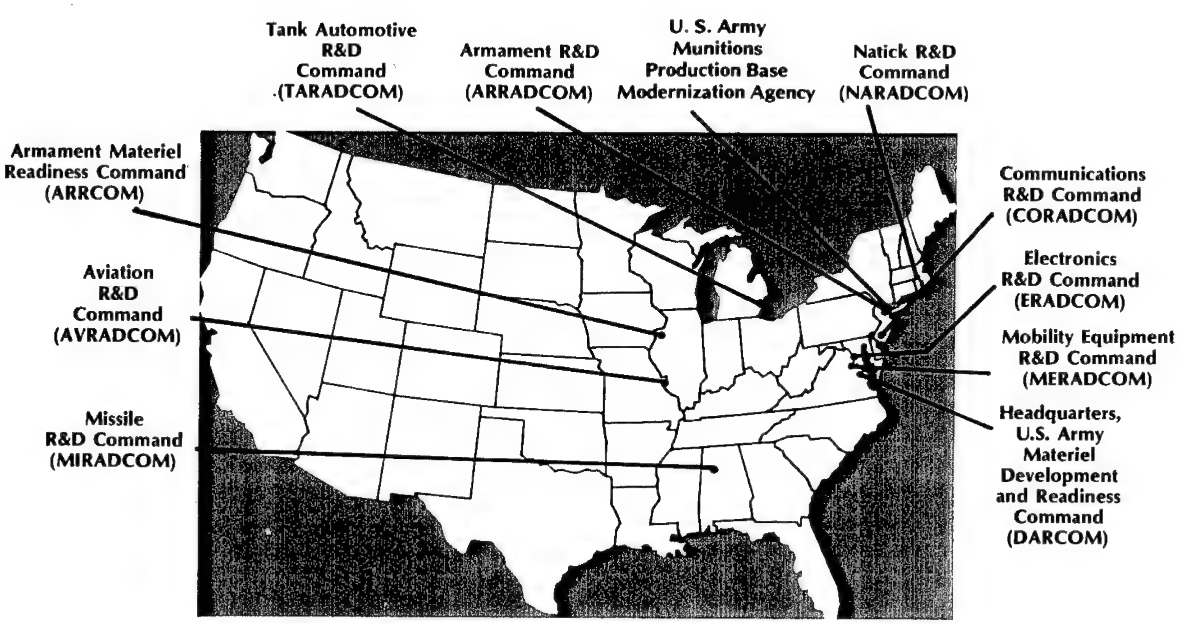
The second parts of two articles that began in the last issue of 1979 are completed in this first issue of 1980—the article beginning on Page 3 about the Army's new MNOS BORAM device and some more of its uses, testing, and fabrication and also the article on Computerized Process Planning at MICOM beginning on Page 20, in which the technology is seen at work and its many future benefits are outlined.

Other articles include a description of Nuclear Metals' rotating electrode process for producing titanium alloy powders using a plasma arc; the evaluation of available NC lathe programming systems by Advanced Computer Systems for CORADCOM; G.E.'s new developments on small turbine blades; Solar Turbine's work on isothermal rolling of aircraft structures; and some new information on rotary forging of precision tubes, a process currently in use which has not been fully exploited for other applications, but for which great potential lies.

Some of the articles just mentioned are the result of the Tri-Service Metals Manufacturing Technology Program Status Review held the past year in Daytona Beach (sponsored by the Metals Subcommittee of MTAG). The three categories addressed at this meeting—Molten Metal Solidification, Wrought Metal Deformation, and Powder Metal Consolidation—will be thoroughly discussed in a series of articles forthcoming in the last three 1980 issues of the Army ManTech Journal. The Subcommittee should be commended for its outstanding presentation of technical material in the three day meeting, which will long be remembered for its thorough organization and coverage of the latest metals manufacturing technology.

Another area of interest to be treated in coming issues of the Army ManTech Journal will be that of foreign technology, with several articles being produced based on papers presented at the 1980 MTAG Meeting in Miami Beach. Also a topic of unusual interest at that meeting was the activity of the academic community in manufacturing technology; several informative articles are in production based on these presentations.

DARCOM Commands Actively Implementing New Manufacturing Technology Methods



New Storage Medium - Greater Safety

WILLIAM H. BOND is a Program Manager with Norden Systems, a subsidiary of United Technologies in Norwalk, Connecticut. Mr. Bond is responsible for the Norden Systems engineering development of the Marine Integrated Fire and Air Support System (MIFASS). He received a B.S. degree in Petroleum Engineering in 1957 from the University of Texas and his M.S. degree in Electrical Engineering in 1969 from the U. S. Naval Postgraduate School.

STANLEY V. LAZECKI is a Senior Electronic Engineer with Norden Systems in Norwalk, Connecticut, where he is responsible for the development of Mass Memory for the Marine Integrated Fire and Air Support System (MIFASS). Mr. Lazecki holds four patents. He received his Dipl. Eng. degrees from the Warsaw Technical Institute and the Grenoble Electrical Institute. He is a member of the Institute of Electronic and Electrical Engineers and the American Association for the Advancement of Science.

HENRY R. ASK is a Program Manager with the Hamilton Standard Division of United Technologies in Windsor Locks, Connecticut. Mr. Ask received a B.S.E.E. degree from the University of Connecticut in 1956. He has been engaged in aircraft systems design and development for a total of 24 years. At Hamilton Standard, Mr. Ask is responsible for the development of advanced flight data recording systems. In addition, he also currently manages an advanced aircraft flight control program.

Editor's Note: This is the second part of a two part article on the MNOS BORAM (Metal Nitride Oxide Semiconductor Block Oriented Random Access Memory) project. The earlier contributors were Joe E. Brewer, Advisory Engineer with the Westinghouse Electric Corporation, and Herbert L. Mette, Leader, Advanced Integrated Circuit Techniques Team, U. S. Army Electronics Technology and Devices Laboratory.

Part II - Testing, Fabrication, Implementation

Extremely small and lightweight—but highly reliable—multichip hybrid circuits developed by Westinghouse Defense and Space Center promise increased savings in various defense systems. As noted in the first part of this article (ManTech Journal, Vol. 4, No. 4), use of the MNOS BORAM circuits in the Accident Information Retrieval System (AIRS) for the Blackhawk helicopter will significantly improve mishap investigation results by making practical the application of flight data recorders to small military aircraft like the AH-64 Attack Helicopter and other aircraft. MNOS BORAM circuits also are being used in a mass storage unit for the Marine Integrated Fire and Support System(MIFASS).

In Part I, development of MNOS BORAM circuits and their manufacturing methods was traced. Part II discusses their integration into AIRS and MIFASS.

ACCIDENT INFORMATION RETRIEVAL SYSTEM

AIRS was developed by Hamilton Standard under contract to Applied Technology Laboratories, U. S. Army Research and Technology Laboratories (AVRADCOM). AIRS consists of an airborne unit called a flight date recorder (FDR), ground readout units, and an existing batch process computer programmed for AIRS data analysis.

Hamilton Standard estimates that the Flight Data Recorder designed with solid state MNOS BORAM circuits is one third the size and one third the weight of a militarized crash survivable magnetic tape recorder, a possible alternate storage medium.

The AIRS FDR is an all solid state digital flight data recorder which interfaces with thirty aircraft sensor signals, conditions and digitizes the sensor signals, and (under microprocessor control) stores the digitized information in a crash protected, nonvolatile, solid state memory device. Use of AIRS will save up to $20,000 per helicopter.
memory device. Use of AIRS will save up to $20,000 per helicopter when considering initial and life cycle cost factor differences compared with conventional tape recorders.

Essential parameters such as accelerations, airspeed, altitude, attitudes, heading, engine power indicating signals, pilot control inputs and fault warning signals are recorded. On newly developed aircraft the majority of these parameters already exist as electrical signals, and the requirement for additional sensors is minimal.

The AIRS FDR conditions analog signals in DC, synchro, and pulse frequency form. In addition, on-off signal information such as fault warning data is accepted. System operation is completely automatic.

Powered From Battery Bus

The system is typically powered directly from the essential battery bus so that the unit is not interrupted during aircraft normal or emergency operations. The unit also will power itself up or down in response to key signals.

An integral solid state power switch is turned on when signals are received indicating that an engine start switch is engaged. The unit deactivates itself in response to sensed helicopter main rotor speed and engine power levels indicating that the aircraft cannot be in flight. A suitable time delay is incorporated to keep the unit recording beyond the low power/low rotor speed condition to make sure that data will be taken for any accident scenario.

Utilizing unique software compression algorithms, the AIRS FDR will preserve the last 15 to 30 minutes of aircraft flight history in a 32K bit storage device. The microcomputer serves as the system controller, built-in tester, and performs the data compression and data transfer to storage functions.

The data compression technique is based on utilizing floating limits in software for each analog input parameter. For example, the microcomputer samples airspeed every second. The current airspeed sample is transferred to protected storage only if airspeed changed by more than five knots from the previously stored sample. Each stored data point includes digital coding to identify the particular parameter and to note when—in relative elapsed time—the data point was taken. For on-off parameters a similar storage action takes place when the parameter changes state. At relatively long fixed intervals (typically, one minute) a complete data frame is committed to permanent storage.

More Flight History Stored

Actual flight test date shows that, by using these techniques, the amount of data committed to permanent storage is reduced by more than a factor of ten without significant information loss. In other words, this method allows ten times more flight history to be stored in a given amount of memory.

When an incident occurs, the stored AIRS FDR data is extracted over an industry standard serial digital link and rerecorded on a cassette based ground readout unit. The cassette is sent to a batch process computer facility for processing. Alternatively, the ground readout unit can also transmit the data over commercial telephone lines. The recovered and processed data can be made available to accident investigators quickly and accurately to augment the investigation process.

CSMM is Heart of AIRS

The heart of the AIRS FDR is the Crash Survivable Memory Module (CSMM), which houses the solid state memory device. The CSMM is a physically separate device which is attached to one wall of the electronics assembly. The electronics assembly can be totally destroyed in a severe accident, while the CSMM is designed to survive extreme crash conditions. The CSMM is a small, lightweight, armored module which is designed to protect the memory device throughout the severe environments of an unsurvivable aircraft incident.

The CSMM is designed using an outer aluminum alloy case for penetration resistance covered with an intumescent coating as the first level of thermal resistance. Inside the aluminum case are four layers of water soaked glass fiber material separated by foil sheets. The layers of water provide the final thermal barriers by maintaining the inner temperature surrounding the memory device near 100 C as the water is progressively boiled off. Formal qualification of the CSMM to the survivability requirements of Federal Aviation Regulation Part 37.150, Technical Standard Order Authorization TSO-C51a, was completed in December, 1979.

MNOS BORAM Memory Increased

The 2K bit MNOS BORAM chips, which are rated for operation from -55 C to 125 C, are packaged in a 16 chip hybrid microcircuit. The chips are part of a series of pin compatible devices designed to go into the same hybrid circuit. The most recent chip in the series contains 8K bits and increases the memory from 32K to 131K bits. Thus, the AIRS flight history can now be expanded from one to two hours' duration.

BORAM Electrical Test Procedures Defined

One of the primary tasks for the MM&T project was to completely define the BORAM product test procedures. In working toward that objective, several intermediate investigations had to be carried out. Four different levels of test were treated: transistors, cell, wafer probe, and hybrids. The threshold decay and pulse response characteristics of memory transistors were investigated using a special test unit called the "VT tester." Test samples were obtained from the test patterns included on each BORAM 6002 die.

Threshold Decay Measured

Figure 1 shows the typical form of the threshold decay characteristic. The upper curve presents the decay of the high conduction threshold or cleared state. The lower curve presents the decay of the low conduction threshold or written state. Threshold voltages are measured at 10 microamps. The abscissa is the read delay time in hours. Hours are used instead of the device physicist's usual practice of seconds, because BORAM retention is specified in hours. The test conditions and the data presentation format were chosen to approximate practical BORAM application conditions.

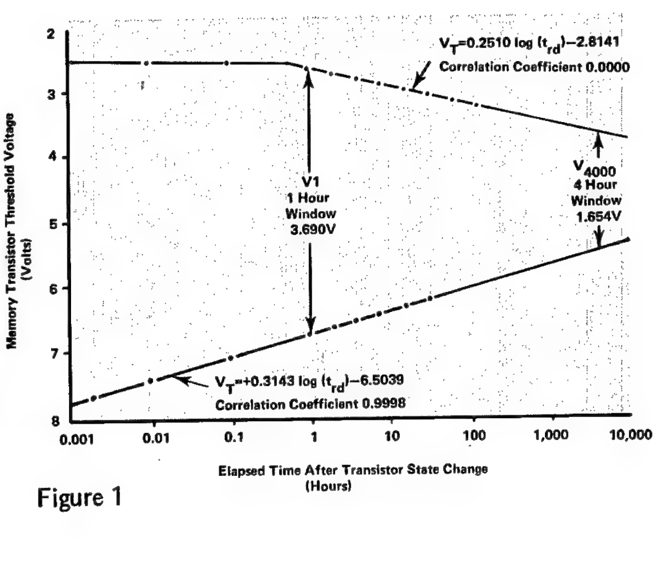


Figure 1

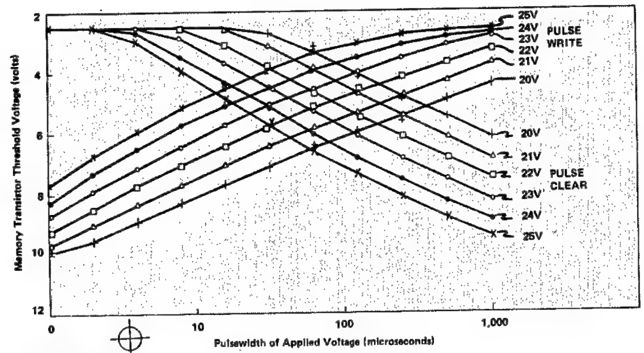


Figure 2

The written state was established by applying a VGS pulse sequence of +25 volts for 3.6 seconds and -25 volts for 128 microseconds, repeated 16 times. Therefore, the transistor is ideally in a saturated clear state prior to the write pulse. The write is generally not sufficient to establish a saturated low conduction threshold.

Observations of the threshold voltage began at 0.001 hours (3.6 seconds) after termination of the write pulse. Additional measurements were taken at 0.01, 0.1, 1, 2, 4, 8, 16, 32, 64, and 128 hours.

The decay characteristic from the cleared state is slightly more complicated. The cleared state was established by a VGS pulse sequence of -25 volts for 3.6 seconds and +25 volts for 1024 microseconds, repeated 16 times. Therefore, the transistor should be a saturated write state prior to application of the final clear pulse. After termination of the final clear pulse, the threshold voltage was observed at 0.001, 0.01, 0.1, 1, 2, 4, 8, 16, 32, 64, and 128 hours.

Pulse Response Characteristics Studied

The pulse response from a saturated state was also explored. Figure 2 shows the write and clear response characteristic curves for six different pulse amplitudes overlayed on one graph. The form of these curves was typical of the population.

The so-called pulse response curve is a plot of threshold voltage against the pulsewidth of the applied gate voltage. Normally, the pulsewidth scale is logarithmic. This means of displaying the dependence of threshold shift on pulse duration has come to be common practice. Quantitative values for a given curve depend on rules for the measurements, and these details must always be clearly stated.

One point on a write pulse response curve is obtained by initially shifting the threshold to a saturated clear level, pulsing the gate with a fixed amplitude and duration write pulse, and then measuring the threshold after a specified time delay. The procedure is repeated with a new pulsewidth to obtain additional data points. A clear response curve is similar, except that the clearing and writing pulses are interchanged.

The Westinghouse VT tester gathers this automatically and stores it in a memory for recall. The read delay time is 3.6 seconds. Pulsewidths follow the sequence 1, 2, 4. . . 512, 1024 microseconds. Thresholds are measured at a drain current of 10 microamperes.

Memory Cell Endurance/Retention Analyzed

A significant experiment on retention time after endurance stress was conducted on Westinghouse BORAM MNOS memory cells. Measurements of retention were collected on 512 BORAM memory cells for over 8,600 hours. Analysis of the data provided a useful guide to application of this MNOS nonvolatile memory product.

The objective of the experiment was to establish the endurance/retention capability of the BORAM MNOS process and memory cell design by collecting retention data on a sufficient number of cells which had been subjected to various endurance stresses. Those memory cells were to be in operating LSI memory arrays, in contrast to previous experiments on isolated single cell or single transistor test structures.

The plan for the experiment was to subject certain memory cells in the memory array of many functional memory devices to various levels of endurance stress and to determine the retention time for those cells. The experiment consisted of three steps. First, 16 cells of the memory array in 16 MNOS parts were subjected to a range of endurance stresses. The 16 cells were in one row in the memory array. Second, a pattern was written into each array. Third, the difference between the two memory transistor threshold voltages were measured for each cell in the stressed row and for an unstressed row at intervals of time after write which extended from 2 hours to over 8,600 hours.

MNOS Test Vehicle

The Westinghouse BORAM MNOS process is used for several electrically alterable nonvolatile memory parts. One of these parts is a l024 bit alterable ROM, called the 1K AROM, mask set number 6020. It was chosen as the test vehicle for this endurance/retention evaluation of the BORAM process because: (1) it has a memory transistor threshold test feature, (2) the memory transistor cell is processed in the same manner as for BORAM memory parts, and (3) the memory cell design is the same as that used in BORAM arrays. The test circuitry incorporated in this part permits making analog measurement of the threshold voltage for each of the two memory transistors per cell in each one of 1024 memory cells in the array.

Figure 3 shows the memory threshold test circuitry as a simplified schematic of the 6020 device. In normal operation, the test enable terminal (T) is LOW, connecting the memory transistor source lines to the detection latch

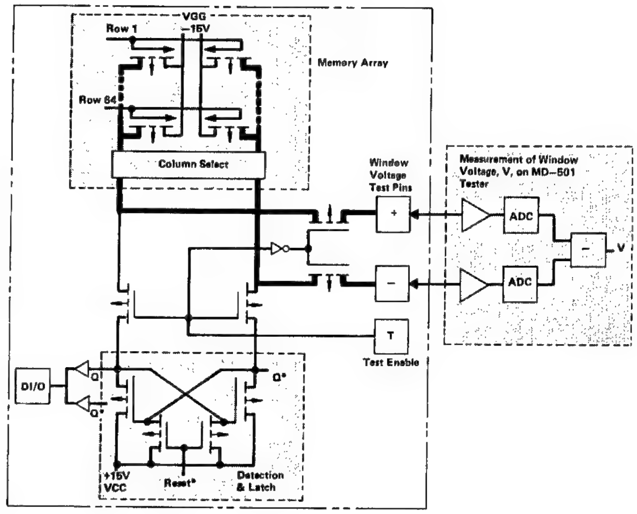


Figure 3

and decoupling the test points (+ and -) from those source lines. When the test enable terminal (T) is HIGH, to enable this memory transistor threshold voltage test feature, the source lines are connected to the test points and decoupled from the detection latch.

Test Procedures Described

The methods and procedures used in this experiment are described in three parts. First is the method of subjecting the parts to endurance stress with some comments on selection of parts. Second is the method of writing each part with the "zero time" retention pattern. Third is the method of measuring the thresholds of the memory transistor.

Endurance Stress Tests

Endurance stress testing for the MNOS parts involved erasing a set of memory cells, writing each cell to a certain state, then erasing the set of cells again and writing each cell to the complementary state. By repetition of these two erase-write cycles, the desired endurance stress is accumulated. These two erase-write cycles have caused each transistor in each of the memory cells to have had one reversal of threshold level, and each transistor can be said to have accumulated one endurance stress cycle.

The 6020 has row erase capability, so that one row of 16 memory cells can be cycle stressed with the remaining 63 rows remaining unstressed. The first row was chosen for cycle stress and the second row was used as an unstressed control row. Parts were stressed using the standard BORAM voltages and erase and write times of 1,000 microsecond erase and 200 microsecond pulse-

width. That row was first erased, then each cell in turn was written, requiring somewhat over 4.2 microseconds per erase-write (16 cells) cycles. Sixteen AROM 6020 parts from two process lots were made available for this experiment. The parts were not screened nor especially selected. A laboratory test set was used to apply repetitive erase-write cycles using a checkerboard pattern. This test set was used for endurance stress; because internal circuitry was designed for CRT display, there is considerable ''dead time'' between stress cycles.

For endurance stresses, a microprocessor controlled burn-in system was used. Programming the KIM-1 microprocessor permitted application of the same BORAM standard timing. The stress pattern written into the first row was 101100. . . (9999 in hexadecimal) and the complement (6666 in hex), on alternate cycles. This system had the advantage of stressing several parts in parallel.

Retention Pattern Write

After the parts were endurance stressed each was erased and written and the time of writing was noted. This is the zero reference time for the retention measurements. Two patterns were used for the retention test. Most parts were written with all ONEs. Several parts were written with a checkerboard (CKBD) pattern. The CKBD pattern was generated by the AND of the least significant row address bit and the least significant column address bit (A0-A4).

Threshold Measurement

An electrical test program written for the Macrodata MD-501 automatic tester was used for all threshold measurements. A sample and hold voltmeter with 100 megohm input impedance was used to measure the voltage at each of the two test points (+ and -). It sampled with an aperture of about 30 nsec, and then held the voltage for the analog to digital conversion. Each test point has a 2- megohm pullup to VCC (+15V) to optimize response and minimize loading. The test program turns power ON, sets up each address in sequence, pulses chip select, waits 50 microseconds for the high impedance measurement to stabilize, then takes the sample at the (+) terminal and converts. Then the program pulses chip select, waits 50 microseconds and takes the sample at the (-) terminal. This sequence continues through all 1024 addresses. The two measurements at each address are subtracted and the absolute value of the difference is printed. Test procedure includes incorporating the serial number of the parts and the date and time of reading with the test printout.

The parts were separated into three groups according to when endurance stress was complete. Readings were taken at one third to one decade intervals of time. The readings spanned a year on 16 parts with 16 stressed memory cells and 16 unstressed cells for a total of 4.49 million memory cell hours of retention data. In the following paragraphs the method of processing the data is described, the results of data evaluation for each part are presented, and the analysis of data for all parts collectively is shown.

Initial Data Processing

The printout from the Macrodata MD-501 automatic tester is a set of 16 voltages per row for each 6020 part for each time of measurement. The values are differences between the threshold voltages of the two memory transistors in a cell, indicative of the memory window. Printout was obtained for the first row, which was endurance stressed, and for the second row, which was unstressed. Some parts were measured at 11 different times, ranging from 30 seconds after write to 8,904 hours (371 days) after write. Other parts were measured eight or ten times covering the same span of time.

Because there is generally a change of decay rate in the vicinity of an hour, the measurements made earlier than 2 hours were not included in the data analysis. From the five to seven sets of printouts for times between 2 and 8,904 hours, five sets were chosen for each part, eliminating some data where the tester or printer was clearly malfunctioning.

The data from the Macrodata MD-501 automatic tester printout and the accompanying accumulated hours since the part was written were entered into an HP9825A computer for tabulation, evaluation, analysis and summary. For each part at each time of measurement, a set of 16 values represented the cells of the stressed row, and a second set of 16 values represented the cells of an unstressed row. This data taken at five different times was assembled by the computer into two 16 by 5 matrices of values. The computer was programmed to compute a least squares fit to a linear equation of the difference voltages as a function of log time for the five data values per cell. Results of this calculation include the slope (decay rate in mV per decade of time), the intercept (window voltage in mV at 1 hour, i.e., zero on the log time axis) and the correlation coefficient of fit to the line. In addition, an estimate of retention time was made using 100 mV as the minimum voltage difference which can be reliably read by the detection circuit in BORAM memory parts. This estimate is simply a calculation of the time at which the straight line fit reaches 100 mV.

The computer stored all this data and results of calculations on magnetic tape for reference. It printed a working data sheet for each part, showing all measurement values in a matrix format and listing the results of the least squares fit. Also calculated were the mean and standard deviation (sigma) for each row of 16 cells for each time of measurement. Finally, a least squares fit to these average values was computed and printed.

Individual Part Data Studied

The 16 samples used for this experiment were chosen randomly from a previously unscreened population. Availability of the computer data summary provided the first opportunity to examine the detail characteristics of each sample and to view the consistency of the data.

Three parts were dropped from the sample because of grossly atypical characteristics which would have caused rejection during normal device screening. The irregularities were small initial windows which differed significantly from that for neighboring cells. The BORAM margin test conducted at reduced write voltage eliminates devices of this nature.

Another observation based upon study of individual cell performance on all parts was that the last two cells in the first row had generally larger voltage differences than all other cells. Specifically, the 16th cell ranked first for 10 of 14 parts. In those parts, the value for the 16th cell was about 3 sigmas above the mean for the row. The value for the 15th cell ranked first for 7 of 14 parts by about 2 sigmas. As a result, the estimates of retention time for these cells are significantly longer, by 2 to 5 decades.

There are layout considerations which indicate that the end memory cells, especially in the first row of the array, could have superior retention performance. Another significant finding gained from measurement of voltage differences on the AROM lab test set was that the Macrodata MD-501 had omitted printout of the reading for cell 0, the first memory cell of the array. Thus the first 15 readings printed by the MD are for memory cell numbers 1 through 15 of the first row and for the first cell of the second row. Because the second row was not stressed, this finding accounts for the 16th reading having a significantly larger value. Clearly, the 16th printout value should be excluded from analysis of stressed cells. Also, for the reasons earlier noted, the 15th printout value, which is the last cell in the first row, should be excluded from further analysis directed toward determining an endurance/retention limit for system applications. Accordingly, the analysis which follows was based upon memory cells 1 through 14 of the stressed row on each part, omitting cells 0 and 15.

Data Analyzed

A working summary of the computations for each part was developed by an additional computer program. The parts were ranked in order of increasing endurance stress and listed with the key parameters for study, plotting and evaluation. This effort was directed toward presentation of the endurance/retention data in a manner which is both informative and useful for applications guidance. The first two parameters of interest were those of the linear fit of window voltage to log time for each part. These parameters, window voltage decay rate and window voltage at 1 hour were plotted vs the endurance stress

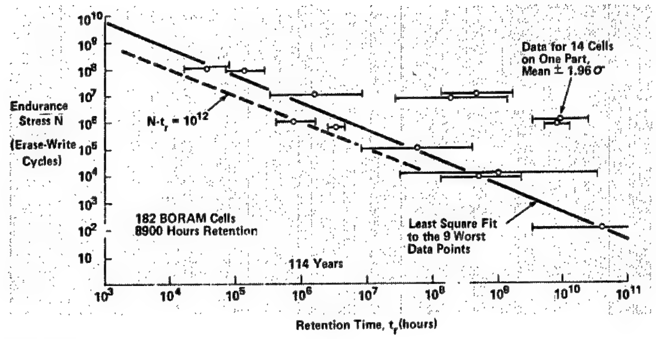


Figure 4

in erase-write cycles. The data is reasonably consistent in that the standard deviations are less than 7 percent of the respective means, generally around 4 percent.

The summary of data for all parts included the estimates of retention time. The standard deviation over the 14 cells of each part was computed. A factor of 1.96 times the standard deviation was plotted to include 95 percent of the population. Actually, because parts on the high side of the mean are of no concern, attention should be focused on the low side. About 97.5 percent of the population should lie above the lower limit. In Figure 4, these estimates and 95 percent range bars are plotted vs the number of erase-write cycles. The four parts stressed are seen to have superior performance. A least squares fit of a line was computed with these four parts excluded. This estimate is very sensitive to the data for each cell of each part. Nevertheless, the line is seen to fit rather well, passing quite near most of the mean values.

Of interest in evaluating endurance/retention performance is a value which has been used as a figure of merit. A dashed line in Figure 4 shows this value. A significant observation is that only a portion of the distribution for only two parts out of the 13 plotted parts lie below the dashed "figure of merit" line.

An observation of some interest and worthy of further study is that the decay rate seems to lessen at longer times. Such can be seen in Figure 1. The calculated decay rate for all five measurements in time is 0.67 volts per decade, but the decay rate between 4,875 hours and 8,713 hours is 0.39 V per decade. This is seen on other parts, to a greater or lesser degree, and has been observed on different MNOS memory device designs. A calculated estimate based upon the last three measurements rather than all five would certainly indicate longer retention time.

Wafer Probe Test

The wafer probe test consists of a sequence of 55 tests which have been divided into six categories. The categories are:

1. Substrate diode tests
2. Functional screen

3. Static parameter tests
4. Retention screen
5. Test structure measurements
6. Pulse response screen.

Category No. 5 tests do not reject material, but merely record data for information purposes. All other tests involve accept-reject decisions. When the status of a given die has been determined it is assigned to a "BIN" by the test equipment. BIN number assignments are as follows.

Test Number(s)	Criteria	BIN
1-1 to 1-16	Fail	10
2-1 to 2-3	Fail	9
2-4 to 2-6	Fail	8
3-1 to 3-12	Fail	7
3-13 to 3-14	Fail	6
3-15 to 3-20	Fail	5
4-1	Fail	4
6-1 to 6-4	Fail	3
6-5 to 6-6	Fail	2
6-7	Fail	1
All Tests	Pass	0

Tests are performed in order by category and number within category. Testing is terminated at the first failure. For a part to qualify for use it must pass all tests and be classified as a "BIN 0" part. The following text documents the circuit conditions for each test. Individual test categories are treated separately.

As shown in Figure 5, the BORAM 6002 contains a fully decoded 64 word by 32 bit RAM and a 32 bit dynamic two phase shift register. All I/O are accomplished serially through the shift register. Parallel bidirectional data transfer between the RAM and the shift register takes place via an internal 32 bit latch. The RAM and shift register can operate independently. Data stored in the latch may be written into the RAM while new data is shifted into the register.

Substrate Diode Tests

Every input terminal to the BORAM chip has an associated substrate diode. Under normal operating conditions where VCC is maintained as the most positive chip voltage, this diode is reverse biased. A similar situation exists for the on-chip test structures except the reference node is SUB rather than VCC, and the GT terminal is isolated (i.e., does not have an associated substrate diode).

The forward voltage drop of the substrate diodes is tested primarily to provide positive evidence of good probe contact to the wafer. In rare cases, however, this test can be an indication of process problems such as inadequate etching, poor ohmic contact, or improper diffusions.

Test Number	General Description of Test
2-1	SHIFT REGISTER TEST 1 MHz data rate zero data pattern
2-2	SHIFT REGISTER TEST 1 MHz data rate one data pattern
2-3	SHIFT REGISTER TEST 1 MHz data rate zero-one data pattern
2-4	ADDRESS & MEMORY TEST 1000 microsecond erase, 200 microsecond write diagonal data pattern
2-5	MEMORY TEST 1000 microsecond erase, 200 microsecond write checkerboard data pattern
2-6	MEMORY TEST 1000 microsecond erase, 200 microsecond write complementary checkerboard data pattern

Table 1

Functional Screen Tests

The purpose of Test Category No. 2 is to eliminate nonfunctional die from further consideration before significant test time has been invested. A sequence of six functional tests are performed at nominal device operating speeds. The shift register is exercised first, then the memory is checked. The first memory test writes unique data into every row address. If this data can be read back correctly, the possibility of a fault in the chip address circuitry has been eliminated. Checkerboard and checkerboard bar tests then verify that every cell can store both ones and zeros.

Table 1 provides a summary outline of the Category No. 2 tests.

Static Parameter Tests

The Category No. 3 test exhaustively examines the device under test for leakage current levels, signal threshold values, output drive capability, and supply current demand. It should be noted that operating power dissipation in a memory system depends on the control waveform timing. Power calculations must consider the duty cycles involved.

Test Category No. 4 was established to isolate chips which are likely to have poor nonvolatile data retention

characteristics. The test simulates end of retention conditions by writing the memory cells using a reduced voltage.

Erase and read are performed at nominal supply voltages and nominal control signal timing. This avoids confusion of circuit operating limitations with possible retention defects.

Test Structure Measurements

The BORAM 6002 die contains some device structures which are not part of the functional memory configuration defined in Figure 5. These structures were provided to allow measurement of fundamental process characteristics and include several capacitors and transistors.

Probe test is a convenient point to gather statistically significant amounts of data without incurring excessive cost. These test structures are not normally available for measurements after device packaging.

In Category No. 5 tests, nonmemory threshold and memory transistor thresholds are monitored. The magnitude of voltage present on the N type epitaxial memory substrate for two circuit operating conditions is also measured.

Pulse Response Screen Tests

Category No. 6 tests are a continuation of the functional screen begun in Category No. 2. A device which has survived up to Category No. 6 has been proven to have in-specification static parameters, to be functional under nominal operating conditions, and to have a reasonable retention window. The purpose of the pulse response screen is to exhaustively examine the part to ensure that it can perform in all operating modes without a detracting dependence on past data history.

HYBRID CIRCUIT TESTING

A functional test station was established to process the BORAM memory microcircuit. This test system provides both manufacturing and engineering oriented reports and is capable of volume throughput in excess of the MM&T production rate requirement.

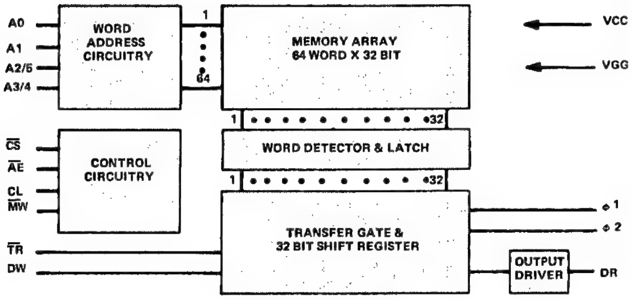


Figure 5

This discussion explains the requirements and objectives of the test station development effort, describes the hardware and software which has been developed, gives the functional test specification, and presents data to show that development objectives were achieved.

The Development Program Outlined

The functional test station must provide specific data in a timely manner in a convenient format. It must with a high confidence level isolate defective chips. In addition, it must comply with the MM&T contract throughput requirement.

The first electrical test of the BORAM hybrid after assembly occurs at Work Station A10. Station A10 is the "Hybrid Circuit Functional Test Station." It is located in the MNOS Test Laboratory at the Westinghouse Advanced Technology Laboratories facility.

At Station A10 the hybrid circuits are unlidded and chip replacement or wire bond replacement actions are feasible. This test station must handle the highest volume of hybrids for any given production quantity because all rework units return to this point.

The purpose of the functional test station is to certify that a given hybird circuit is fully operational and is suitable for further processing; in the event of a detected failure, the purpose of the test station is to provide information to guide rework decisions.

Test Requirement

The functional test is a test of unfinished product performed for manufacturing decision making purposes. The test criteria are thus a function of the manufacturer's judgment as to how to determine that the product is functioning properly with a minimum expenditure of test time.

The nature of the manufacturing decisions at Station A10 dictates the report requirements. The needs of the technician who must diagnose the probable cause of a detected failure must be met.

The rework action is best served by a simple hard copy report which clearly identifies the chip or chips which must be visually examined and possibly replaced. Preferably, this document should be small enough to travel with the normal hybrid circuit routing ticket documentation package. It would be helpful if the chips were identified in a manner consistent with the actual physical locations of the die on the ceramic substrate. This feature would tend to reduce human errors in device location.

To examine individual station throughput requirements, it is convenient to express the rate specification in hybrids per hour. A nominal month by the above operating criteria contains 160 hours. Therefore, the line rate requirement is 11.7 hybrids per hour.

The functional test station must process every hybrid circuit at least two times. Each device is tested before

and after cycle stress. In addition to these two tests per hybrid, any rework action implies two additional tests per hybrid.

Other Objectives

The primary concern is the rapid screening of the BORAM hybrid at Operation 10 in the hybrid assembly and test flow. There are, however, test considerations of importance to BORAM production which are beyond the scope of Operation 10 and yet should influence the design of the test system.

The production of BORAM systems involves memory testing at four levels of product complexity:

a. Memory Chips
b. Multichip Hybrids
c. Memory Cards or Modules
d. Memory Systems

These tests are very similar. It would be a major advantage if the test system designed for hybrid test could also conveniently perform the other three levels of test.

Finally, the test system design must consider the practical aspects common to all equipment developments. Hardware cost and reliability must be reasonable. Software development and documentation must be easily accomplished without major labor expenditures.

Functional Test Station Described

The BORAM Functional Test Station is based on an architectural concept which contributes greatly to economy and ease of use. The system is suitable for application to all four levels of BORAM testing. This discussion explains the design concept, describes the hardware, reviews the hardware operation, examines the software functions, and briefly describes the microcode assembler used to support software development.

The fundamental architectural concept on which the design of the Functional Test Station is based is to partition the test problem into two parts: a "macrolevel" and a "microlevel". Figure 6 illustrates the points of concern for each level.

The macrolevel is concerned with overall test objectives and the human oriented requirements. Macrolevel software acts as the executive controller for the test. Macrolevel hardware interacts directly with the user.

The microlevel is concerned with the execution of the detailed control sequences for accomplishing device operation. Microlevel software responds to macrolevel commands to accomplish a required function. Given the command "WRITE," the microcode might proceed to write a complex data pattern into an assembly of memory chips. Microlevel hardware interfaces to the macrolevel hardware and to the device under test. The microlevel hardware must provide the proper voltage levels, waveshapes and timing.

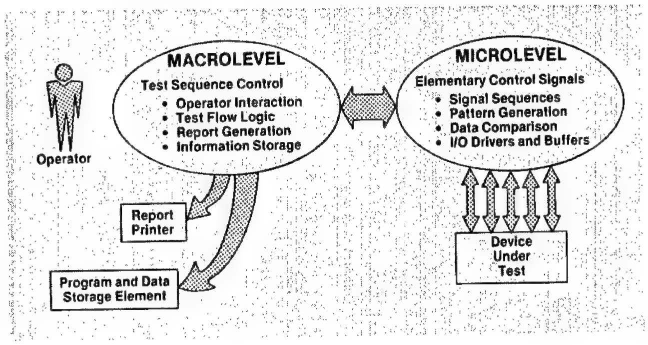


Figure 6

The advantage of this partitioning is that each set of problems becomes easier to treat. The flexibility of both the hardware and the software is greatly increased.

Test Station Elements

Figure 7 shows the hardware elements used to implement the Functional Test Station. The primary macrolevel component is an HP9825A calculator. This device is an inexpensive yet very powerful general purpose computer.

HP9825A programs are written in a high level language with many of the features of BASIC. The calculator mainframe incorporates an alphanumeric keyboard, a magnetic tape cassette drive, a 32 character LED display, and a paper tape printer. Extensive program editing and debugging features are built into the unit. The particular HP9825A used in the Functional Test Station is equipped with 23,228 bytes of main memory.

The I/O capability of the calculator is further supplemented by an HP9866B Thermal Line Printer. This unit is used to prepare the test reports.

Program and data storage are accomplished using the tape cartridge feature of the HP9825A mainframe. The tape capacity is more than adequate to store both macrolevel and microlevel programs as well as many utility routines.

The microlevel component in the system is the BORAM Functional Test Unit (FTU) shown in the foreground of Figure 7. This device communicates with the HP9825A via a 16 bit channel. This is the cable at the left side of the unit. Two channels are provided to communicate with devices under test. In Figure 7, the two cables at the right

of the unit are shown connected to PC boards which can accommodate 30 integrated circuits for test.

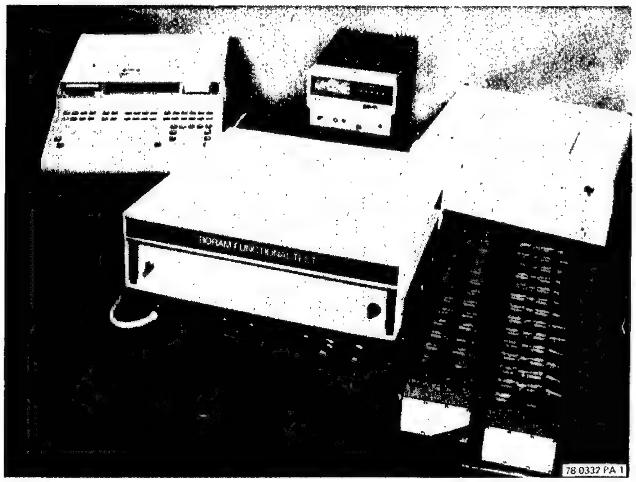


Figure 7

The block diagram shown in Figure 8 describes the internal structure of the BORAM Functional Test Unit. A microcontroller based on the Am2911 microsequencer chip forms the heart of the test unit.

During the initialization phase of the test, the HP9825A reads the microcode program from the tape cartridge and sends it via the 16 bit bus to the Functional Test Unit. The microcode is stored in a RAM. This feature makes the unit particularly easy to use and to reconfigure. The option of microcode storage in ROM's or PROM's was also allowed for in the hardware design.

The interface to the device under test necessarily involves specific waveshapes and voltage levels. The output circuits on the driver cards, the address card and data pattern card accomplish this function.

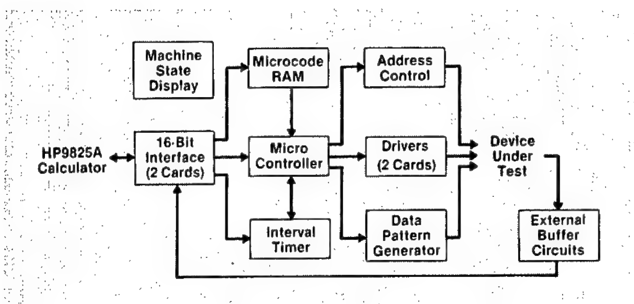


Figure 8

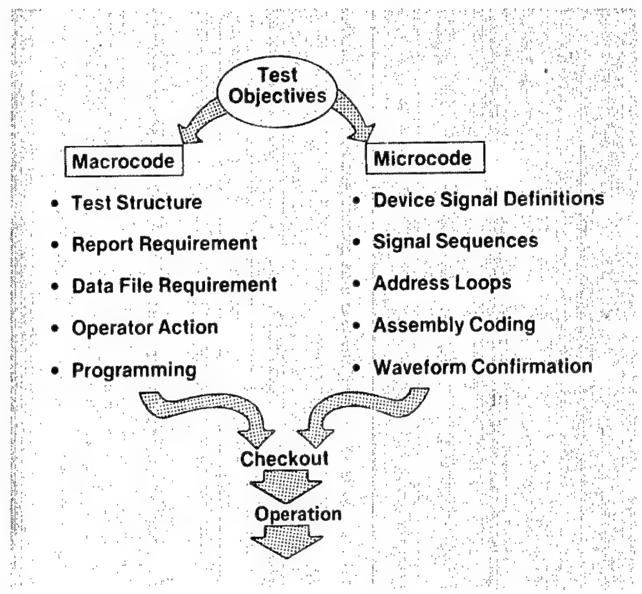


Figure 9

Software Considerations

For operation the Functional Test Station requires two sets of software programs. Figure 9 gives an overview of the programming task. The macrolevel program runs on the HP9825A. The microlevel program runs on the microcontroller in the Functional Test Unit.

The software development begins with a clear statement of test objectives. What is it that must be achieved? The macro planning activity extends these requirements into specific definitions of the test sequence and output reports. Then the desired tests are detailed in terms of tape file storage, main memory variable assignments, and operator interaction requirements. Finally, the actual coding can be performed.

Functional Test Station Performance

The microcircuit has two data inputs (DWA and DWB) and two data outputs (DRA and DRB). The "A" data lines are associated with the eight odd numbered chips. The "B" data lines are associated with the eight even numbered chips. Each chip select line controls one odd and one even numbered device. Data outputs are tristate. A deselected chip is powered down, and its DR output line is in a high impedance state. In the hybrid circuit only one odd and one even chip may be selected at any given time. The selected chip controls the output bus and has both active source and sink capability.

Test Reports Production Oriented

The test reports indicate the pass or fail status of each of the 16 chips in the hybrid. It is intended that the reports for each hybrid will be cut apart and will travel with the

normal routing ticket documentation. The technician in charge of rework will locate a chip to be repaired using this report.

Test results are printed on the report in a manner which matches the physical location of the die on the hybrid substrate. This similarity in orientation was established to reduce the possibilities for human error in locating a specific die.

The engineering report is intended to allow a diagnosis of possible circuit problems to guide rework action. To use this tool the engineer or technician must be familiar with the nature of the individual tests.

As an example consider the results for Chip 06 in Hybrid 00015. This chip passed the counter pattern, erase recovery-checkerboard bar, zero pattern, one pattern, and read disturb tests. This implies that the chip functions properly. All wires must be in place, and all on-chip circuitry must operate. The chip failed the erase recovery-checkerboard tests. This implies that some memory transistor(s) are slow in recovery from multiple clearing. Thus in this case the rework action required is to replace the chip. In other cases, the combination of test results may indicate a wire bond problem, and detailed visual inspection would be called for.

Throughput Observations

The throughput capacity of the BORAM functional test station has been examined by formulating the sequence of actions an operator must perform and by timing each individual action.

In this experiment, the actions were performed by engineers who had no significant previous experience with the detailed motions involved. Because the engineers lack the dexterity which would be acquired by a test operator, the observed times are believed to be pessimistic.

The scenario for a test operator involves two phases. A "start-up activity" sequence prepares the test system and the first group of eight hybrids for test. An "operating activity" maintains a continuous flow of hybrids through the test system by repeating a sequence of operations. It is assumed that the operator is continuously being given a supply of hybrids to be tested and that hybrids which have been tested are removed together with the test reports by other personnel.

A working assumption is that hybrids are brought to the test station in a container in groups of eight. The container also accommodates the routing ticket and other traveling manufacturing documentation. Each hybrid is labeled by a control number or serial number easily seen by the operator.

The operator's responsibility is to see that each hybrid is tested and that the hybrids are returned to the proper container with the test reports. The serial numbers on the reports uniquely relate the data to the part.

MNOS BORAM FABRICATION

The MNOS BORAM hybrid circuit packaging approach was conceived to provide low cost, high density and growth potential simultaneously. A baseline fabrication approach was established which made use of previously defined materials, processes and tooling. At the same time each element of hybrid was defined to easily allow the introduction of new materials, processes and tooling. During the course of the MM&T project several improvements were introduced, and several others have been defined and are being developed.

The MNOS BORAM hybrid is approximately one by two inches, and it contains 16 BORAM monolithic integrated circuits. Both the physical and electrical configuration of the hybrid are important to the achievement of low cost manufacture.

The initial configuration of the 647R527G01 hybrid circuit is shown in Figure 10. A 24 pin metal case houses an epoxy bonded alumina substrate. The multilayer substrate provides the interconnection pattern for 16 epoxy bonded 6002 chips. A hermetic seal is achieved by using a solder preform to attach a lid to the metal case.

The configuration of the 647R527G01 hybrid was modified during the MM&T to incorporate the use of a welded lid and to change some dimensional details of the metal case.

A significant advantage of the BORAM hybrid electrical configuration is that it does not impose any serious constraints on the hybrid circuit fabrication approach. Close control of impedance levels, propagation delays and crosstalk is not necessary for proper circuit operation.

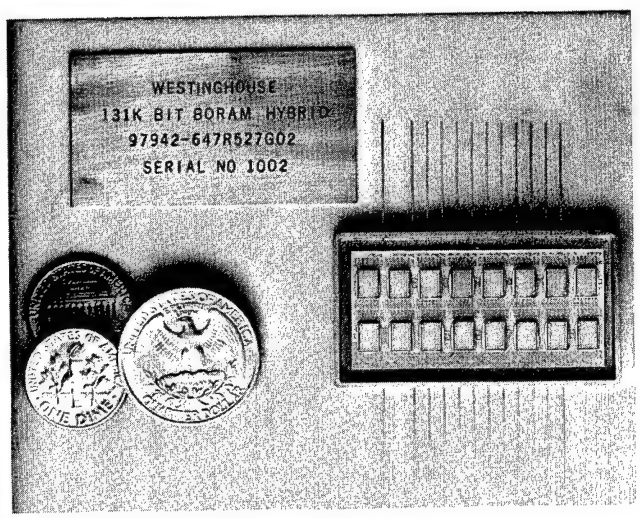
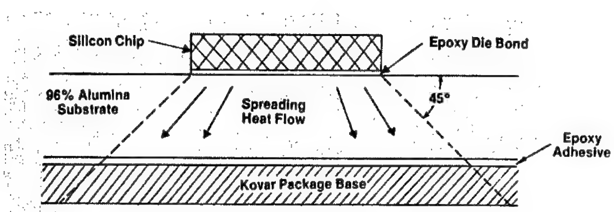


Figure 10



$$\Theta_{JC} = \Theta_{silicon} + \Theta_{epoxy\,1} + \Theta_{alumina} + \Theta_{epoxy\,2} + \Theta_{kovar}$$

Figure 11

The input terminals of 6002 chips are high impedance lines, and thus series input resistance is not critical. Input capacitance is not critical either, but it should be held to low levels to avoid placing excessive demands on external driver circuitry.

Circuit reliability is dependent on the thermal characteristics of the packaging approach. Early in the MM&T program approximate thermal models were developed to ensure that proper consideration was given to this important factor.

Figure 11 shows the thermal situation for one chip within the hybrid. The chips are positioned sufficiently far apart and have such a low duty cycle that thermal interaction should be negligible.

The model predicts 10.59 C/watt for a single die. Since two chips are active at any given time, the hybrid circuit thermal resistance is 5.3 C/watt. Because of a change in alumina substrate thickness, a more recent version of the hybrid circuit has a thermal resistance less than 5 C/watt.

Many fabrication options exist for the substrate. The particular implementation chosen was compatible with existing Westinghouse processes and tooling.

The substrate dimensions are 1.700 by 0.780 inches. Interconnection is accomplished by four metal layers. The layers are separated by and supported by a dielectric material. Layer to layer interconnections are made by 0.015 by 0.015 inch vias. The top metal layer is exposed, and provides pads for wire bonding.

The base material is alumina. For MM&T production the alumina was 0.040 inch thick. More recently it has become possible to reduce the alumina thickness to 0.020 inch.

Multiple Substrate Screening Used

To reduce the labor content of substrate manufacture, six hybrid circuit substrates were silkscreened on a single piece of alumina. After completion of all screening and firing operations the individual substrates were separated by a sawing.

Layout of the top layer of the substrate allowed the use of conventional wire bonding or tape bonding. The pads were defined to accept tape carrier versions of the 2K bit, 8K bit, and larger chips in the 6000 series.

Each substrate is tested for interconnect pattern continuity. Both opens and shorts are screened. The equipment employed for MM&T production is called a Flying Head Probe. This equipment employs two probes that are moved from point to point under computer control. Probing paths are optimized by software during programming. The final control program is stored on a magnetic tape cartridge.

Packaging Economical and Reliable

A metal case was chosen for the BORAM hybrid circuit primarily because of its cost potential. The package external dimensions were selected to maintain compatibility with tooling for previously developed ceramic packages.

Economy and reliability can be achieved when packages are manufactured in volume for multiple users. To promote this situation, Westinghouse strives to reduce the variability in package use by establishing standard options for designers.

The basic specification for the BORAM hybrid metal case establishes the materials, processing and quality assurance provisions for a family of packages.

Flexibility in package definition and room for growth is maintained by allowing various package options to be specified without altering the basic specification. One such feature under current study is the option of using nickel coated cases instead of gold coating. Elimination of gold can mean a significant cost saving. Procurement options are specified by suffix digits on the package part number.

Chip Lead Bonding Utilized

The initial approach employed for connecting the BORAM chip pads to the appropriate pads on the substrate was a manual technique. An operator would use 0.001 inch gold wire in an ultrasonic bonder to connect each chip. The use of ultrasonics avoided high temperatures during processing.

Later, the throughput and reliability of bonding was improved by the introduction of a computer controlled wire bonder. The automatic wire bonder consists of an ultrasonic bonder, a master console, a disk memory, an operator's control pendant and a power supply.

Computer controlled bonding was used with good results during the pilot production run. The machine achieves bonding speeds at least six times faster than that of a manual station.

In the future tape bonding will be employed for BORAM hybrids. During the time period of the MM&T, but under separate funding. Westinghouse has fabricated and tested tape carrier BORAM hybrids.

Several aspects of the tape carrier technology have motivated its development for BORAM. This approach should lower assembly costs by direct automation and by

reduction of rework. It also holds promise for an increase in reliability because of greatly increased bond strength. Gold 0.001 inch wire bonds have a typical bond strength of less than 6 grams. Tape bonds typically show bond strength greater than 50 grams.

The availability of tape mounted chips makes it possible to test and burn in every chip before it is inserted into a hybrid package. This capability is expected to sharply reduce the need for removal of chips from the hybrid after initial assembly and to reduce the failure rate through hybrid package burn-in.

MARINE INTEGRATED FIRE AND AIR SUPPORT SYSTEM

The Marine Integrated Fire and Air Support System (MIFASS) is a force multiplier that gives optimum control and coordination of supporting arms with instant response capability. Simple and easy to use, MIFASS delivers real-time solutions to real-time problems. The system is being developed by Norden Systems, the military and space systems subsidiary of United Technologies.

Norden's MIFASS is responsible to the commander and ensures rapid, close coordination of all fire support and troop maneuvers. Inherent in the system is its ability to provide fast, flexible fire planning and execution. During combat of all levels of intensity, MIFASS provides significantly improved response time.

System Expansion Planned

Future development of the next member of the BORAM family by Westinghouse in a form of 32K bit chip will permit memory expansion to 4 M words with minimal electrical modification and without any change in power consumption, weight, and volume.

The Mass Memory will be completed in April, 1981. Early testing commenced at Norden in November, 1980, using depopulated memory cards based on individual integrated circuits.

Mass Memory Module the Key

To fulfill these demanding requirements, MIFASS employs the AN/AYK-14 microcomputer supported by the Westinghouse BORAM 8K MNOS integrated circuit. The Mass Memory is the key to the MIFASS software concept of storing in nonvolatile memory all of the computer programs for the CMOS memory AN/AYK-14 microcomputer (see Figure 12).

The MIFASS Mass Memory being developed by Norden is based on storage modules using hybrid circuits containing 16 BORAM 8K MNOS integrated circuits. Six storage modules provide the full mass memory complement of greater than a three quarter of a million word storage. It required nonvolatile secondary memory with the capacity 0.75 M words, expandable to 1.0 M word operation at typical temperature conditions from -30 C to 85 C. These requirements are easily met with MNOS storage medium in the form of the Westinghouse BORAM 6008 chip. BORAM chips are assembled in 16 chip hybrids; 18 such hybrids with associated control and interface circuitry from a 128K work module assembly. MIFASS Memory can use up to 8 such assemblies for the total capacity of 1.0 M words of 16 bits each.

Low Power Required

In order to enhance the endurance of the memory system the retention (nonvolatility) is controlled between 300 and 4000 hours. The storage modules with associated controller and power supply consume approximately 5 watts from the external power source at a typical system interrogation rate. This low power consumption is obtained by internal electronic power switching of controller and storage modules. Power switching provides a significant improvement in system reliability—predicted for well over 4000 hours of MTBF.

The reliability is enhanced by a special error detection and error correction mechanism operating with 64/72 EDC format. The external communication of the Mass Memory in MIFASS system is obtained via input/output unit, consuming approximately 5 watts and operating externally on dual serial bus T/R twisted pair cables. Expected weight and volume of the Mass Memory is 24 pounds and 0.68 cubic feet in a water sealed enclosure for full portability. Mass Memory is equipped with extensive 'built-in test facilities to simplify field maintenance problems.

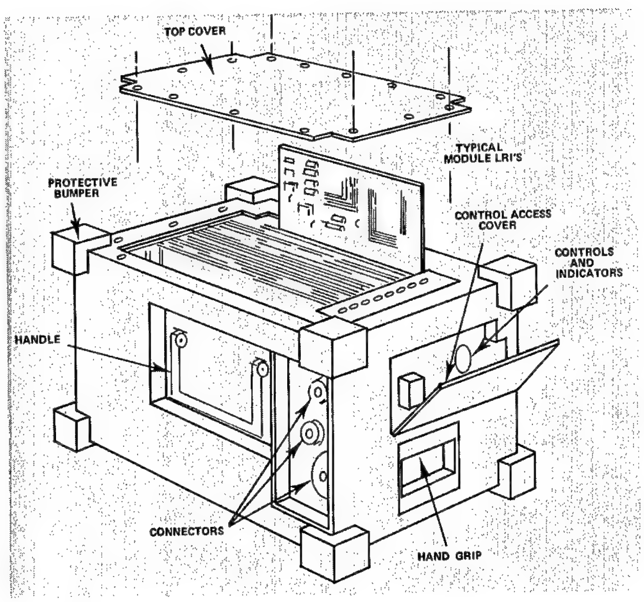


Figure 12

Plasma Arc Improves PM Process

Tungsten Free Ti Powder

PAUL LOEWENSTEIN is Vice President and Technical Director, Nuclear Metals, Inc., Concord, Massachusetts. Mr. Loewenstein received his M.E. at Stevens Institute of Technology. He is well recognized for his contributions to the fields of metalworking, powder metallurgy, and casting. Most recently, he has been active in the development of non-nuclear uses of depleted uranium. Mr. Loewenstein is a Fellow of The American Society of Metals. He has developed a number of specialized modern metal working processes. In the areas of plastic working, he has been active in extrusion, rolling, forging, drawing, swaging, tube reducing, and other aspects of hot and cold working of metals. In the field of melting he has had experience with vacuum and atmospheric induction melting, arc melting, and the production of metal powders. He has been intimately involved in the development of production processes for high quality spherical powders by the REP (Rotating Electrode Process) and by the PREP (Plasma Rotating Electrode Process). Mr. Loewenstein is the author of numerous technical and scientific papers and has contributed chapters to the following reference books: "The Metallurgy of Zirconium"; "The Metal Beryllium"; "Nuclear Reactor Fuel Elements Metallurgy and Fabrication"; Reactor Handbook (Vol. 1)"; and "Ceramic Fabrication Processes".

Using a plasma arc with the rotating electrode process (REP), Nuclear Metals, Incorporated is producing titanium alloy powders with extremely low tungsten content. The low tungsten powders are important in hot isostatic pressing (HIP) of turbine engine and airframe components for many high strength applications. Extensive support from the U. S. Air Force and U. S. Navy manufacturing technology programs has helped make this process a production reality. Although HIP has helped to reduce costs of such parts and to conserve material, tungsten inclusions from the cathode used in REP powder manufacture have reportedly reduced fatigue life in titanium alloys heat treated to high strength levels.

Extensive efforts to eliminate tungsten contamination entirely have met with little success. Now, the plasma arc approach appears to answer the problem while producing powder similar in all respects (except tungsten content) to that produced by conventional REP. Tungsten levels in powder manufactured in this way are comparable to those in the starting titanium electrode stock.

Hip Improves Material Utilization

Titanium alloys are assuming an increasingly important role in manufacture of vital aircraft components. But they also are the most costly materials used on an engineering scale. Furthermore, the present titanium supply is critically short. Thus, improved material utilization is vital. The most promising method to increase material yields, reduce part costs, and possibly improve properties of titanium alloy components is the pressing of powders to near net shape using HIP. Development of that process requires titanium powders that combine high bulk density, low surface area, and an extreme degree of cleanliness. That need appears to be best met by the rotating electrode process; conventional gas atomization will not produce the required cleanliness level, since molten titanium reacts with all known crucible materials. Other methods are under development, but REP powders have been in production for many years and have been used extensively in many near net shape parts produced by HIP.

Basic REP Process

The basic rotating electrode process for producing spherical powders is illustrated in Figure 1. Processing takes place in a sealed, helium filled chamber. A bar of the metal or alloy to be made into powder is rotated at high velocity—typically, 15,000 rpm. The end of the bar is melted by a heat source such as an electric arc, a plasma arc, or an electron beam. Molten metal is ejected from the bar, solidifies into fine droplets, and collects in the containment vessel.

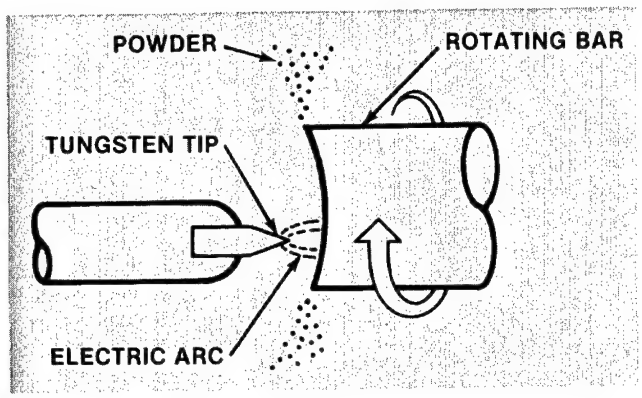


Figure 1

There are two standard variants of the basic process—short bar and long bar. The short bar machine (shown in Figure 2) accepts consumable electrodes (anodes) that may be up to 3½ inches in diameter and 10 inches long. The entire consumable electrode and the collet or chuck in which it is held are contained within the machine chamber. After most of the anode has been converted to powder, the operator removes the 1 to 2 inch anode "stub" through a glove port and replaces it with a new anode.

The short bar machine is very useful for short runs and for experimental alloys that may be available only in short lengths of various diameters. Its productivity, however, is not nearly as high as that of the long bar version.

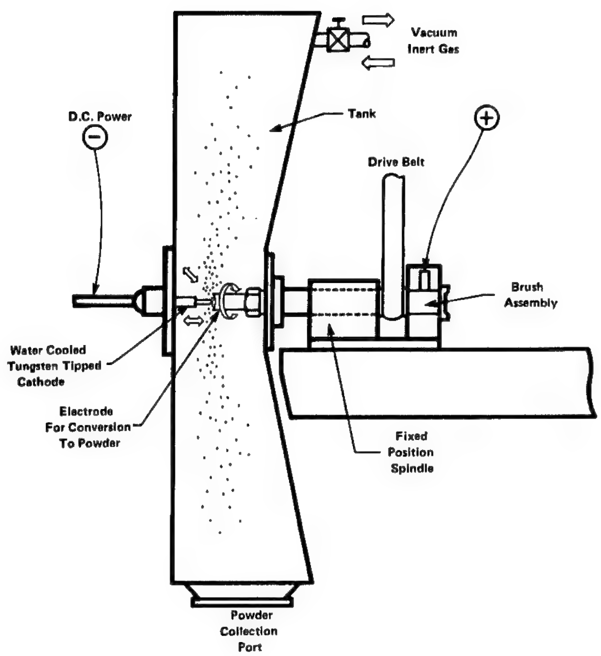


Figure 2

Long bar machines accept 2½ inch diameter anodes up to 72 inches long. The anodes are processed in the chamber but are held by a collet that is located outside and behind the machine, as seen in Figure 3. The rotating electrode enters the chamber through a gas tight dynamic seal and is advanced into the arc by the operator. When most of the anode is consumed, the collet is opened and retracted. A fresh anode is then loaded and advanced behind the first. The long bar machines are far more efficient, with very little time lost loading fresh electrodes and a much smaller percentage of material lost in stubs.

Tungsten Contamination A Problem

By ordinary standards, the quality of REP powders produced on presently available equipment is very good. In most less demanding applications, properties of parts made from the REP powder are equivalent to or better than those of parts made from cast and wrought metal. However, with today's higher strength titanium alloys, inclusions that were acceptable with earlier more ductile alloys can no longer be tolerated. REP powders have been shown to contain inclusions, both metallic and non-metallic, that reduce the potential fatigue life of parts made from them. Most metallic inclusions are attributable to cross contamination arising from use of the machine for manufacturing powders from other metals. Non-metallic inclusions result from external atmospheric contamination. Both situations can be closely controlled with proper process controls. The problem of tungsten inclusions from the process cathode is not so simply met, however.

The conventional REP machine uses a water cooled tungsten tip as the cathode of the electric arc. Although this electrode is considered nonconsumable for most practical purposes, a small amount of tungsten erosion does occur. In addition, some of the titanium powder contacts and contaminates the tungsten tip, forming a titanium-tungsten alloy. When ejected as a powder particle, this alloy solidifies to precipitate a tungsten rich region in the powder.

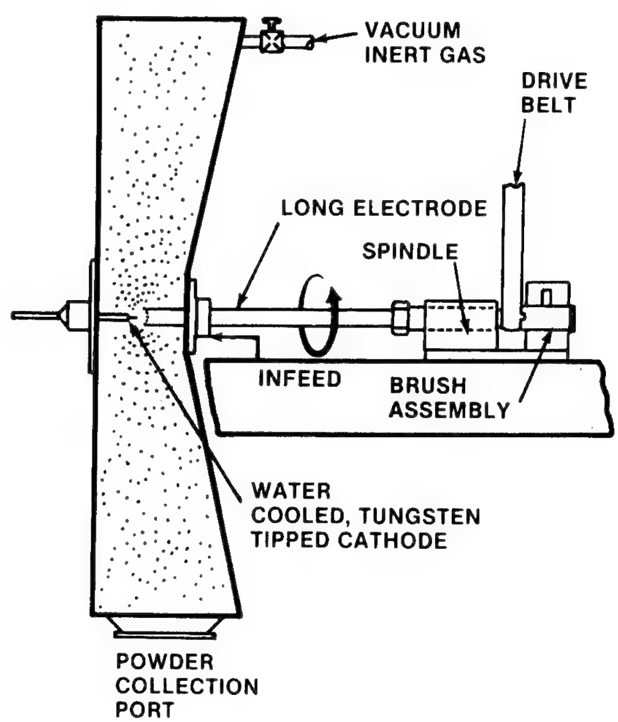


Figure 3

Contamination to Be Eliminated

Most titanium alloys contain up to 10 ppm tungsten in a solid solution. Chemical analysis of some REP powder lots has revealed an increase in tungsten content of up to 400 ppm. Recent efforts have reduced tungsten contamination to 10 to 20 ppm above that of the starting stock. At present, Ti-6Al-4V REP powder is regularly produced that contains less than 50 ppm of tungsten. Even these levels are not always acceptable; however, the goal is to eliminate tungsten contamination entirely.

The Air Force has supported attempts to do this by replacing the cathode with a second rotating, consumable titanium alloy electrode. Initially, difficulties were encountered in maintaining an arc between the dual electrodes since the electrical emissivity of titanium is very poor when compared to tungsten. But eventually, a steady arc system that produced titanium powder was developed. Unfortunately, the arc from the titanium cathode produces a small quantity of titanium and its alloying elements in the vapor phase. This titanium vapor condenses into an "ultrafine" powder, which is pyrophoric, oxidizes rapidly, and makes the produce essentially unusable.

All efforts to eliminate the ultrafines either by suppressing their generation or by removing them from the chamber or the powder proved unsuccessful. Therefore, after a long experimental program, all work on the double electrode process was terminated.

Plasma Arc Solves Problem

Nuclear Metals has now developed a plasma arc heat source for the REP machine. Using this approach, titanium alloy powders comparable in quality to those produced with the tungsten arc, but essentially free of deleterious tungsten inclusions, are produced.

The principle of the transfer plasma arc is shown in Figure 4. The plasma gun consists of a water cooled tungsten cathode and a copper nozzle. Helium flows between these two components. A low current ignition arc in the nontransfer mode is struck initially between the tungsten and the nozzle. The ignition arc heats the helium until it becomes ionized and initiates the transfer arc between the cathode and titanium anode. The helium plasma, carrying between 500 and 1000 amperes, melts the rotating electrode to produce powder as in the conventional REP machine.

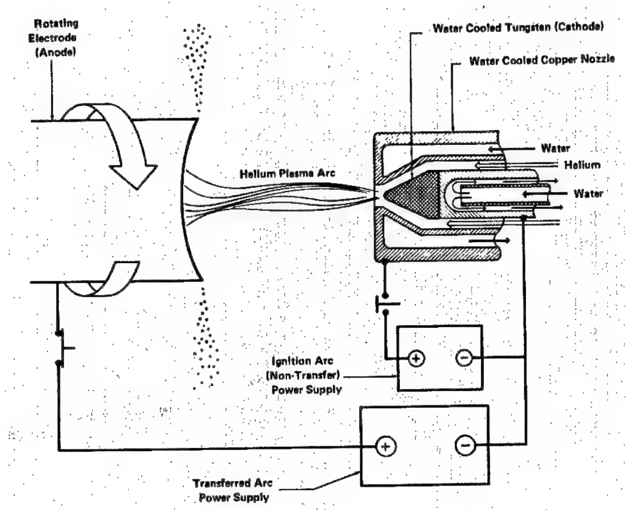


Figure 4

The work so far has shown that there is extremely little tungsten loss from the plasma gun. The tungsten is probably vaporized in the arc and will not form harmful particles in the titanium powder. This is confirmed by chemical analysis of the powder, which shows an increase in tungsten content of less than 5 ppm compared to the starting electrode. In all other respects, the powder is similar to that produced by the conventional process. Low tungsten extruded samples have shown improved ultimate tensile and yield strength and generally better ductility than samples with higher tungsten content.

Production Plans

Nuclear Metals has designed and installed a dedicated production facility using the plasma arc approach to the rotating electrode process. This facility has a powder producing capacity of 6,000-10,000 lb/month (one shift operation). It includes a long bar/short bar machine in a room pressurized with filtered air and an inert atmosphere powder processing train. Powders are transferred from the machine to the processing train in sealed, inert atmosphere containers and ultimately are shipped to users in sealed containers either in filtered air or in argon. This facility went into operation in the Fall of 1980.

Production Efficiency Boosted

Computerized Process

Computerized process planning technology very well may remake industrial production systems worldwide. Interest in programming computers to generate process plans for manufacturing parts is growing and involves not only the defense industry but public and private sectors as well.

Computerized Production Process Planning (CPPP) is a process planning system developed for the U. S. Army Missile Command by United Technologies Research Center. The system assists process planners in formulating the production of machined cylindrical parts.

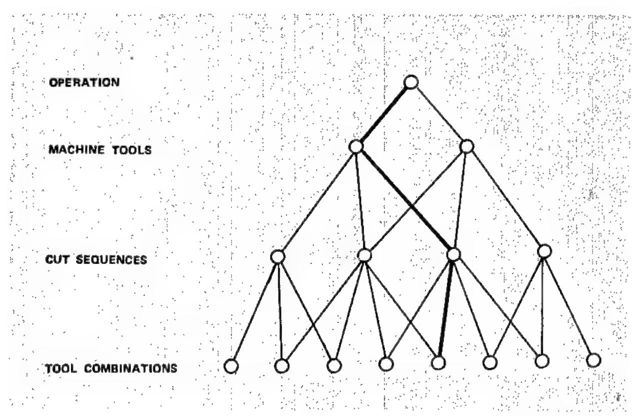
CPPP was developed and implemented to show how a process planner working at a graphic display terminal could develop a process plan for a nitralloy sleeve. A process model and data base were developed for a part family of nitralloy sleeves manufactured by the Hamilton Standard Division of United Technologies. The family includes components of the JFC78 Fuel Control for the General Electric T700 engine, which was selected to power the Army UTTAS helicopter being developed by Sikorsky Aircraft.

Part I of this article (Army ManTech Journal, Vol. 4, No. 4) examined the basic concepts of CPPP technology, including process planning, software and hardware systems, process models, and other CPPP concepts. In the concluding Part II, CPPP technology at work, man/machine communications, and CPPP benefits are some of the topics discussed.

Process Planner Chooses

The CPPP operation detailing function provides detailed information for each operation in the sequence of operations. The task of the detailing module is to determine the best machine tool (if a particular one is not specified), best cut sequence, best cutting tools, and best machining parameters to use for each operation. In initiating CPPP, the process planner must indicate whether he wishes these choices made to minimize machining time or machining cost.

As illustrated in Figure 1, this task is one of finding the best path through a network of possible choices. The figure shows two machine tools that could be used for the operation. Each machine tool has three possible cut sequences, with two cut sequences being possible on both machines. The four cut sequences have respectively three, four, four, and three possible tool combinations, two of which are unique to one sequence and the other six of which are shared by two sequences.



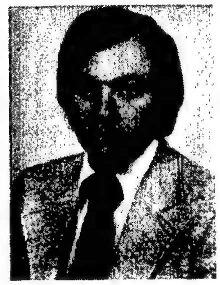
OBJECTIVE: FIND THE PATH OF MINIMUM TIME OR COST

Figure 1

Best Combination Also Best Cost

The cost (or time) of the operation on a machine tool is that of the best cut sequence on that machine tool. The cost of a sequence is in turn that of the best combination of cutting tools operating at chosen feeds, speeds,

RICHARD A. KOTLER is Manager, Manufacturing Technology, Engineering Directorate of the U. S. Army Missile Command. After joining MICOM following his graduation in 1967 from Tennessee Technological University in Industrial Engineering, he has held continually more responsible positions in numerical control and computer aided manufacturing programs, printed circuits, and hybrid microcircuits; he is a member of the International Society for Hybrid Microcircuits. He received his MBA from Vanderbilt this past year, and serves as Coordinator of Command MICOM Manufacturing Methods and Technology programs.



Planning – Part II

and cut depths. The heavy line in the figure represents the best choice. To identify the best path in the network, all paths must be generated, examined, and evaluated.

The nine functions that must be performed to arrive at the best path through the network are given in the following list. Successive levels of indentation indicate successive levels of functional nesting. For example, level two is repeated several times to solve level one and each repetition of level two requires several repetitions of level three.

1. Determine machine tool candidates
2. Determine cut sequence candidate
3. Determine types of cuts
4. Determine cutting tool candidates
5. Calculate machining parameters
6. Formulate cutting tool combinations
7. Select best combination of cutting tools
8. Select best cut sequence
9. Select best machine tool

Functions 1 and 9 are performed once per operation; 2 and 8 are performed for each machine tool candidate. Functions 3, 6, and 7 are performed for every cut sequence considered in the operation; 4 and 5 are performed for each cut in every sequence.

The main emphasis in generating operation details has been development of the analytic framework necessary to perform the job. The current mode of operation relies heavily on interaction by the process planner to steer CPPP away from consideration of bad or uninteresting possibilities. The detailing modules are not yet fully developed and do not operate from stored process logic as the initial operation sequencing modules do. As a result, CPPP must generate and examine several different logical possibilities at each detailing step and must attempt by time and cost estimates to make good selections. The estimates rely heavily on machinability analysis and values from the CPPP data base. The present system requires a manufacturer to estimate many data base values used in the analysis. Ultimately, these estimates should be replaced by more accurate methods of calculating the data values. Thus CPPP might expend considerable effort making estimates from poor data and make a poor choice if unaided by interaction by the process planner.

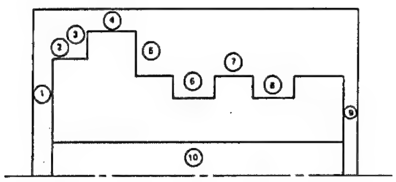
Complete Workshop Data Stored

A solid framework has, however, been developed for CPPP operation detailing. This framework is dependent on having a description of each metalcutting and nonmetalcutting operation that has been included in the sequence. For metalcutting operations the description consists of the type of operation, type of machine tool—lathe, grinder, hone, etc., the surfaces that are to be cut and the workpiece geometry. For nonmetalcutting operations such as heat treating, plating, coating, or inspection, it consists only of the operation type and machine type—furnace, bench, etc. In addition to this information about the sequence to be planned, the detailing cycle requires complete information about the workshop. This data must include information about available machine tools, tooling resources, stock removals and tolerances for different cutting situations, and machinability. All of this workshop dependent information must be stored in the CPPP data base, from where it can be retrieved for operation detailing. The data is passed along in the form of an "operations matrix," a summary list of the operation descriptions, and the geometry of the raw material and finished workpiece.

Figure 2 shows a sample part. The first six operations on such a part, as found in the summary list of operation descriptions, might be as follows:

Op 10—Draw barstock from raw material stores
Op 20—Turn to rough shape and cutoff
Op 30—Heat treat to stress relieve
Op 40—Centerless grind locating diameter

Op 50—Gun drill through bore
Op 60—Rough turn the cutoff end
This partial sequence of operations will be used to discuss the operation matrix, also shown in Figure 2.



Operation Data						Affected Surfaces									
Op. No.	MCT	Setup	MC1	MC2	MT	E001	D002	F003	D004	F005	D006	G007	G008	E009	I010
10	-1	N	100	0	108	0	0	0	0	0	0	0	0	0	0
20	1	N	400	0	0	1	0	0	1	1	1	0	0	1	0
30	-1	N	300	0	301	0	0	0	0	0	0	0	0	0	0
40	5	N	500	0	0	0	0	0	0	1	1	0	0	0	0
50	2	R	600	0	0	0	0	0	0	0	0	0	0	0	1
60	1	R	2400	2500	0	1	1	1	1	0	0	0	0	0	0

Figure 2

Three Hierarchy Levels Recognized

At the top of Figure 2, the final part geometry is shown superimposed on a section of barstock. The part illustrated has an open outside diameter, two stepped outside diameters, two grooves, a through bore, and two ends. These surfaces are numbered in a clockwise fashion starting with the left end. By adding "E" for end, "D" for diameter, "F" for face, "G" for groove, and "I" for internal diameter to these surface numbers, the four character CPPP surface names are formed—E001, D002, F003, etc. The labels appear in the operations matrix.

At the bottom of Figure 2 is the beginning segment of the operations matrix for this part. There is a matrix row for each operation, and the illustration shows the initial six operations described in the preceding sentence. The operations matrix consists of two parts. The first five columns are for general operation data. The remaining columns, one for each part surface, tell which surfaces are cut or affected by the operation. The first column, MCT, identifies the type of machine class to be used. CPPP recognizes a hierarchy of three levels of machine classification. At the bottom is the identity of specific machine tools such as B&S No. 2 Automatic Bar Machine or Micromatic 723 Automatic Hone. The middle level groups machine tools into classes such as automatic bar machines and automatic hones. The top level groups machine classes by types such as lathe and hone. MCT is a code representing this top level. The MCT Code -1 is used for noncutting equipment such as benches, tanks, and furnaces; 1 is the code for all types of lathes; 2 is for deep hole drills; 5 is for cylindrical grinders; and so on.

The SETUP column determines whether the part is in Normal orientation as shown in the picture or in Reverse orientation for the operation. The MC1 and MC2 columns give the internal code numbers of the primary and, if specified, alternate machine class for the operation. For example, 400 is the code for bar machines, and 2400 and 2500 are the codes for automatic and NC chuckers. The MT column may specify a particular machine tool for the operation. In the figure a raw material bench (MT = 108) is specified for Operation 10 and a stress relief furnace (MT = 301) for Operation 30. The remaining columns (affected surfaces) have a 1 to indicate a surface is cut in an operation or a 0 to indicate it is not. A 1 is also used to indicate that a surface is affected by a special process, such as nitriding or nickel plating.

Machine Tool Candidates Determined

To determine the qualified machine tool candidates for an operation, CPPP first examines the MC1, MC2, and MT columns of the cut matrix. An entry in MT will cause the specified machine tool to be the only candidate and it is automatically qualified. Otherwise, all machine tools listed in the data base under the machine class identified in MC1 become possible candidates. If MC2 specifies an alternate class, all its machine tools are also included.

The possible list of candidate machine tools is then examined, one machine at a time, and those which qualify for the operation become part of the final list of qualified machines. Machines from the original list qualify for an operation if they can physically accommodate the workpiece and can perform the required cuts. The present version of CPPP disqualifies a machine tool only if the overall part length or diameter is too large or small or if some special feature—such as bore diameter for a gun drilling operation—is out of range. However, information is now available in the CPPP machine tool file and part design data to support more detailed analysis in the selection of qualified machine tools. For example, machines with horsepower ratings below a certain value could be eliminated for certain hard to machine materials. The types of cuts and their tolerance and finish requirements could also be used to restrict the number of machines

considered. It is of practical importance to limit this number because a machining analysis is performed for each machine and can result in appreciable computer costs.

After qualification is finished, the operation will be fully detailed on every qualified machine tool to determine which is the best one.

Cut Sequences Chosen

The first step in identifying cut sequences is for CPPP to determine the aggregate material to be removed in the operation. Figure 3 shows the stock removal for Operation 20 of the cut matrix in Figure 2. From this figure it is easily seen that while there are five cut surfaces—E001, D004, F005, D006, and E009—there will be only four cuts because D006 and F005 must be formed together from solid condition. CPPP recognizes these four cuts and orders them into different cutting sequences. Logically there are 24 possible sequences of the four cuts, but some of these are physically impossible and others may not be good machining practice. For example, the eighteen logical possibilities that place E001 first, second, or third in the sequence are physically impossible because barstock cutoff must be the last cut in the operation.

If the grooves were also formed in this operation, it would generally be preferable to cut them after D006 to avoid an interrupted cut on the diameter and to avoid cutting excess stock in a forming operation. It would also be logically possible to cut either groove first, thus doubling the number of possible cut sequences to be considered without adding anything of interest. For these reasons it is necessary for CPPP to apply some manufacturing intelligence to limit the number of candidate cut sequences. Bar machines in general require cutoff to be the last cut. Swiss automatics and tracer lathes require a single right to left cutting pass. On any manual machine it is important to cut the datum reference surface for the operation first. These are all examples of intelligence that are not yet implemented in CPPP, but which have been partially identified and can be further developed.

What CPPP actually does is to follow heuristic rules to subdivide the total stock to be removed into regions. The regions themselves are ordered and are then each broken down into a subset of ordered cuts. The procedure used makes all rough cuts before any finish cuts, cuts diameters before forming grooves in them, etc. While these heuristics are being improved and eventually re-

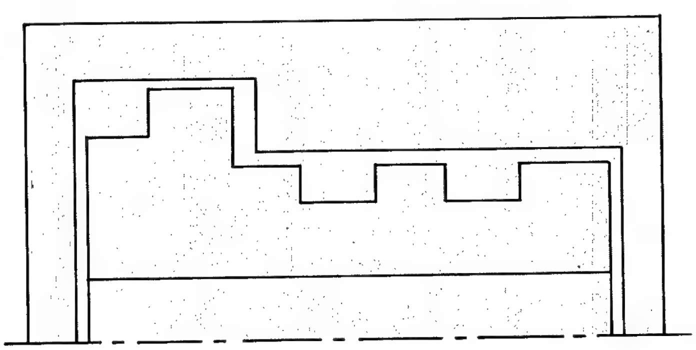
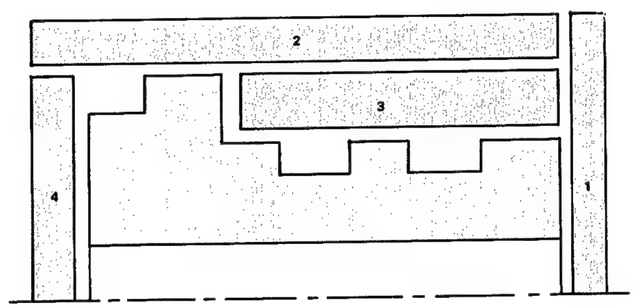
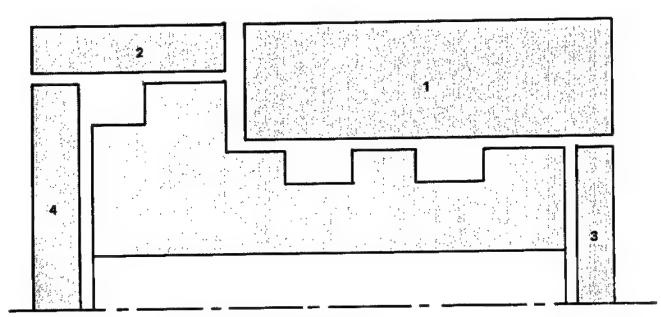


Figure 3



CUT SEQUENCE: E009, D004, D006, F005, E001



CUT SEQUENCE: D006, F005, E009, D004, E001

Figure 4

placed by process decision logic, the process planner can use the CPPP interactive capability to modify or specify the cut sequence candidates.

When the cut sequence candidates have been determined, each one is further detailed in turn. Any one of the cut sequences is an ordered list of the surfaces to be cut and implies a breakdown or decomposition of the material to be removed. Decompositions for two cut sequences are shown in Figure 4.

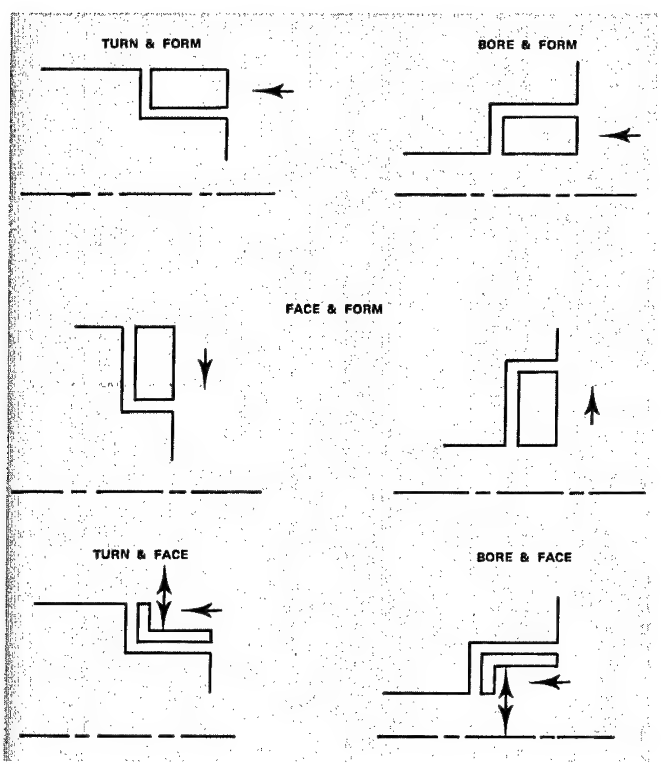


Figure 5

Types of Cuts Selected

The next problem for CPPP is to recognize the material decomposition for a cut sequence and to determine the type of cut represented by each element of the decomposition. To select appropriate cutter tools and to estimate cutting time and cost, CPPP must know the type of cut. Under the CPPP philosophy, each workshop is allowed to specify the types of cut each machine tool can make. For each cut type defined, a computer program is written and made part of the library of cut types known to CPPP. Figure 5 shows examples of some cuts included in the CPPP cut library.

A list of all the cut types each machine tool can perform is stored in the CPPP data base. When a particular sequence of cuts is being considered for a particular machine tool, CPPP steps through the list of that machine's cut types. For each one it executes the corresponding library program on the first cut surface until one of them recognizes the first surface as its specific cut type. CPPP then advances to the second surface in the sequence, and so on. Figure 6 shows the result of this activity—each cut has been identified by type. Also, the nominal stock removal can be determined for each cut and whether it is a rough, semifinish, or finish cut.

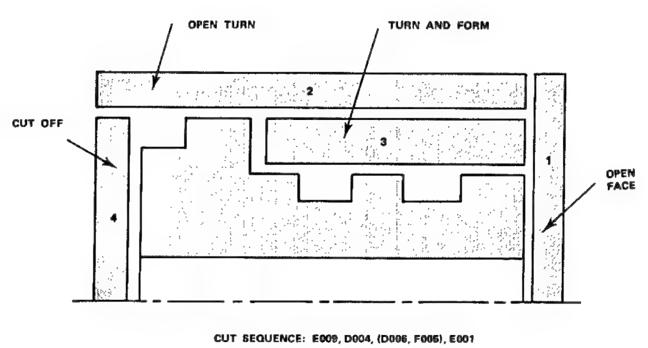
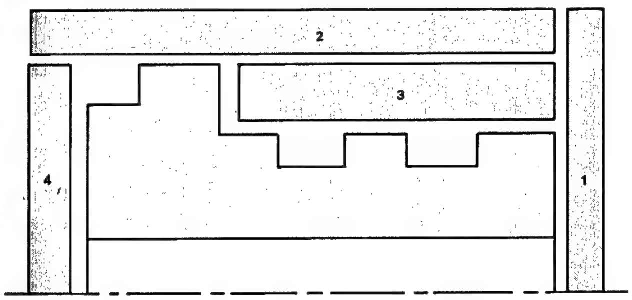


Figure 6

Cutting Tool Candidates Picked

CPPP was designed to support two methods of cutting tool selection. Only one is currently implemented—selection of types of tools based on the machine tool and the type of cut. Along with the list of cuts each machine tool can make, the CPPP cata base includes one or more cutting tool candidates for each of the machine's cut types.

The second method is a capability for retrieving specific alternate tools using stored process logic from the data base. However, this capability is not being used by the present demonstration system. Either concept results in the situation illustrated in Figure 7, wherein each cut has a corresponding list of cutting tool candidates.



CUT	SURFACES	CUT TYPE	CUTTING TOOLS		
1	E009	OPEN FACE	TOOL–1	TOOL–2	
2	D004	OPEN TURN	TOOL–1	TOOL–3	
3	D006,F005	TURN & FORM	TOOL–1	TOOL–3	TOOL–4
4	E001	CUTOFF	TOOL–5		

Figure 7

Machining Parameters Calculated

Each cut is analyzed to determine its feed, speed, depth of cut, and number of cutting passes. These machining parameters are included as part of the detailed data on the operation sheets for metalcutting operations. They are also needed to calculate production times and costs. The CPPP framework repeats this analysis of machining parameters not once per cut, but for every cutting tool candidate for each cut. Although CPPP does currently select only tool types and not actual cutters, this provision is made to allow the subsequent addition of actual cutter selection. When the actual cutter and its geometry are known, they become important parts of the overall cutting situation and can alter the machining parameter results. In particular, the shape and size of single point turning tools limit the maximum depth of cut per cutter pass.

Cutting Tool Combinations Formulated

Under consideration is a particular sequence of cuts on a particular machine tool. A list of candidate cutters has been determined for each type of cut. This means there are several possible combinations of cutter tools that can be used. Picking one candidate from each list gives a particular cutting tool combination. It is important to consider these combinations because on some machines the correct choice of the best tool for one cut, in theory, cannot be made without knowing the tools for the other cuts. For example, on a manual or NC machine it could be possible to reduce the total number of tools and save turret indexing time by using the same tool for more then one cut.

CPPP formulates the possible combinations and calculates the resulting operation time and cost for each. Essentially, this builds up a subnetwork problem as shown in Figure 8. Proper evaluation of the network requires more data resources than are available in the demonstration CPPP. For example, if more than one tool is mounted on a single tool post to make multiple cuts at the same time, the recommended feeds must be adjusted to make them the same and equal to an available machine tool setting. After that, the cost of the tooling for the cuts is the sum of the tooling cost of each, but the total time is only the time of one single machine stroke. A similar situation arises when two separate tool posts operate simultaneously. However, CPPP cannot yet perform this analysis because it has no information on tool layout and simultaneous cutting.

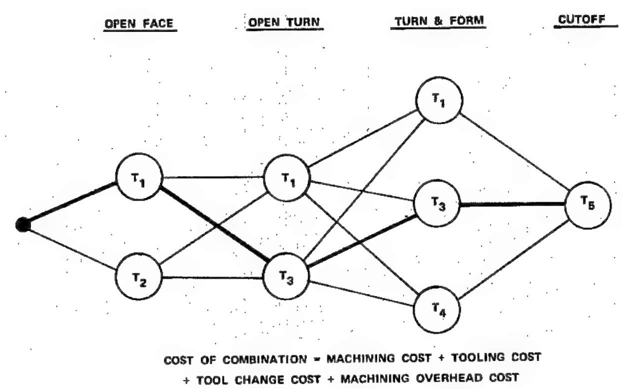


Figure 8

Best Detailing Selected

CPPP detail planning analyzes individual combinations of cutting tools carefully. These analyses are repeated many times to cover all combinations of alternate candidates. When each level of analysis is completed, CPPP makes a process decision. There are three levels at which decisions must be made.

(1) Each candidate cut sequence may have several candidate tool combinations. When each tool

combination has been analyzed and assigned time and cost estimates, the best tool combination is chosen. The process planner must inform the system at the start whether he wants "best" to mean least time or least cost. Its time, cost, and detailing information become the detail data for that particular candidate cut sequence and are saved while CPPP analyzes other cut sequence candidates.

(2) After each candidate cut sequence has been analyzed by detailing its candidate tool combinations and selecting the best, CPPP selects the best cut sequence. The time and cost data for each are reviewed to find the best sequence. That sequence with its tools becomes the tentative detailing of the operation on that particular machine tool and is stored for later consideration. CPPP then repeats the detailing procedure on the remaining machine tool candidates.

(3) When a cut sequence, tool combination, and the resulting time and cost have been determined for each machine tool candidate, CPPP selects the machine to use for the operation. Again this is the candidate with the lowest time or cost. The detailing on the chosen candidate becomes the final detailing of the operation.

This procedure of economic analysis is repeated for every metalcutting operation. Nonmetallcutting operations are handled similarly but much more simply because there is no cut sequence or cutting tool combination. When the last operation has been detailed, the detailed operation plan lacks only final dimensions and tolerances for the intermediate workpiece geometry of each operation. Subsequent subsystems of CPPP calculate dimensions and tolerances and produce the finished process plan.

Man/Machine Communications

The CPPP communication medium is a low cost terminal with line drawing and text capabilities that can be located away from the computer in the process planning area. CPPP has been designed so that no computer skills are required for the process planner to operate the system and process planning, as seen by the user at the terminal, progresses in a familiar manner. Part sketches are heavily used to communicate the status and progress of planning. Communication is conversational. Response to user input ranges from almost instantaneous to a few seconds if adequate computer support is provided. Several levels of interaction are available—the process planner can choose among these according to the completeness and correctness of the manufacturing data base, his confidence in CPPP, and his own work habits.

The terminal is connected to a general purpose computer system on which CPPP is implemented. In response to directions input at the terminal, the computer system accesses data in the manufacturing data base, uses this data to execute CPPP code, transmits graphic displays which inform the process planner of the status of planning and options available to him, and stores the process plan data that is generated. CPPP currently is implemented for TEKTRONIX 4006, 4010, 4012, and 4014 graphic terminals. These may be connected to the computer by voice grade (telephone or intercom) lines or by more specialized lines. The terminal may be very close to or distant from the computer.

CPPP Modes of Operation

The process planner can choose among three CPPP modes of operation which offer different degrees of user involvement. Confidence in the CPPP data base, especially process decision models, will usually determine the desired mode.

The highest level of automation is **fully automatic** process planning. In this mode CPPP uses coded manufacturing rules, other manufacturing data, and part designs to generate complete process plans without human intervention. Most obviously, this level is used to prepare process plans when there is full confidence in the system. When confidence is less than total, it may be practical to use this mode to generate a "first pass" plan which can be studied before generating a final plan and also for make-or-buy, producibility, and cost estimating studies.

If the data base is somewhat less than complete or there is not full confidence in its correctness, **semiautomatic** process planning is appropriate. In this mode, process planning is performed by CPPP with the user overseeing and, to the extent desired, modifying the plan as it is developed. The user may select the degree of supervision he wishes to exercise by specifying the points at which he desires to interact with the system.

When process decision models are unavailable or the process planner wishes to investigate radically different processes, **interactive** process planning may be used. In this mode the user supplies the sequence of operations, after which the system helps to provide a detailed plan

for each operation. As with the semiautomatic mode, various degrees of interaction are available.

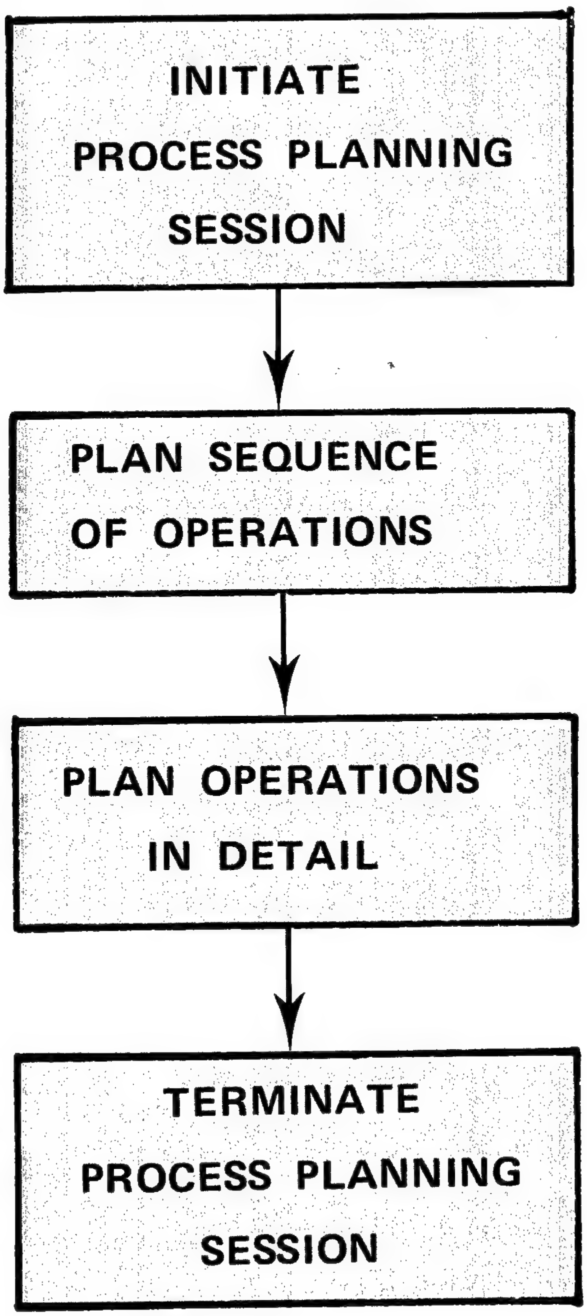


Figure 9

Interaction Points Enable Planning

There are fifteen major points where the user can interact with CPPP. To describe the role of these interaction points, a skeletal review of the system's processing is appropriate. Figure 9 gives a high level view. The process planner initiates a CPPP session by entering basic data and instructions. A sequence of operations is then produced. For each operation, operation type, machine class(es) or particular machine tool, setup orientation, and surfaces to be affected are determined.

When the sequence of operations is complete, each operation is planned in detail. Alternative machine tools are identified. For each machine tool, alternative cut sequences are generated. For each cut in each sequence, alternative tooling is identified. The operation is then planned for various tooling combinations, with time and cost calculated. The best tooling combination for each cut sequence, then the best cut sequence for each machine, then the best machine for the operation are chosen. The detailed plan for that operation is then stored and the next operation attacked in the same manner. Once all operations have been planned in detail, the process plan is complete and the planning session is terminated.

Cost Benefits Tangible

CPPP benefits were projected to defense agencies using the assumption that defense suppliers' savings and costs are passed along to procuring agencies. Benefits were estimated in three procurement areas: Army missiles, over Army equipment, and Department of Defense equipment. Discounted cash flow analyses for the period FY78 through FY87 were performed.

Three analyses, offering three different points of view, were performed. The first shows CPPP's full savings potential. Procurement savings were calculated assuming use of the system by all defense suppliers. A second analysis was performed, using a realistic projection of CPPP usage by industry. In both of these analyses, it was assumed that the full investment was made (by individual defense suppliers) at the start of the time period and that full benefits were realized immediately. This is a common method for avoiding problematical estimates of investment and benefit phasing. An industry implementation schedule was estimated and used in the cash flow analysis.

Cylindrical Part Data Lacking

The CPPP system is currently applicable only to machined cylindrical parts. It was, therefore, necessary to estimate procurement costs for these parts. These were estimated as the product of two factors: (1) total procurement budget and (2) the percentage attributable to machined cylindrical parts.

To estimate total procurement costs, actual and projected procurement budgets published by the Office of Management and Budget were obtained. After considering the trends of the 1974 through 1978 budgets, it was decided that an annual increase of approximately 10 percent could be expected. Hence, procurement costs for 1979 through 1987 were estimated using 1978 as a base year and a 10 percent increase factor. The 1978 base estimates were $657 million for Army missiles, $6.342 billion for all Army equipment, and $35.143 billion for Department of Defense equipment.

Very few data were available on the portion of procurement costs attributable to machined cylindrical parts. Companies were asked to estimate the value of machined cylindrical parts as a fraction of total product value. The average response for missile contractors was 12.1 percent. In a case study presented at the Missile Manufacturing Technology Conference in 1975, machined parts (including noncylindrical) accounted for 14 percent of the standard hours for production of a missile. From this evidence, it was estimated that machined cylindrical parts represent 10 percent of Army missile procurement costs. Cylindrical component costs for overall Army and Department of Defense procurement were extrapolated from the estimate for missiles. Machined cylindrical parts are clearly a smaller portion of costs in many major procurement areas of these agencies—ammunition, weapons, tracked vehicles, ships, etc. Hence, it was estimated that 5 percent of Army and Department of Defense procurement is attributable to cylindrical parts.

The investment required of defense suppliers implementing CPPP and the resulting benefits were derived from the analyses for "model" defense manufacturers. For the demonstration CPPP, implementation costs for the three companies averaged 1.30 percent of annual costs for cylindrical part fabrication. The corresponding figure for the advanced system was 2.99 percent. Net savings, with full system utilization, were 3.15 percent for the demonstration CPPP and 5.45 percent for the advanced capability.

Cash flow analyses were performed using the parameters above and assuming use of CPPP by all defense manufacturers. The results, shown in Table 1, give an estimate of CPPP's potential to reduce procurement costs.

	Demonstration CPPP		Advanced CPPP	
Agency	Undiscounted ($ millions)	Discounted ($ millions)	Undiscounted ($ millions)	Discounted ($ millions)
Army (Missiles)	32.129	18.878	55.102	32.176
Army	155.071	91.116	265.949	155.296
Department of Defense	859.297	504.901	1473.703	860.541

Table 1

Time, Cost Related

The same method was used for a second analysis, except that a projection of CPPP use by defense industry was factored into the calculations. Such an estimate is, of course, highly judgmental. The survey response shows a favorable opinion of the system's savings potential. There are, however, many obstacles to widespread adoption of a single system. The willingness of suitable organizations to commercialize the system, future enhancements funded by industry or government, and the success of alternative systems are important factors. Use of the system by 15 percent of defense industry was felt to be a reasonable estimate. Use of this factor resulted in the savings estimates of Table 2.

In the third analysis of defense procurement benefits, time phased realization of savings was considered. There are two time factors that affect the achievement of procurement savings. First, adoption of the CPPP system by defense industry would occur over a period of time. Second, cost reductions obtained by an individual defense

supplier are dependent on the amount of time elapsed since that company started implementation.

Estimation of an industry implementation schedule was, of course, highly judgmental. It was felt that (1) implementation before FY79 is unlikely, (2) ultimate use of CPPP by about 15 percent of defense machining industry is a reasonable projection, and (3) implementation will occur, at an increasing rate, over several years. This rationale yielded the schedule shown in Table 3.

There is a striking difference between the results in Table 2 and those in Table 4, which shows total savings for the period for each CPPP capability and procurement area. This is primarily due to the short period of system usefulness implicit in the latter analysis. In that analysis, the average period of CPPP implementation and use is only six years. In the first two or three of these years, implementation costs exceed savings. Hence, there are only three or four years during which savings are obtained. In the analysis of Table 2, full savings were obtained during the entire ten year period.

Fiscal Year	New Implementation, percent	Cumulative Implementation, percent
1979	1	1
1980	1	2
1981	3	5
1982	5	10
1983	5	15

Table 3

	Demonstration CPPP		Advanced CPPP	
Agency	Undiscounted ($ millions)	Discounted ($ millions)	Undiscounted ($ millions)	Discounted ($ millions)
Army (Missiles)	4.819	2.832	8.265	4.826
Army	23.261	13.668	39.892	23.295
Department of Defense	128.895	75.736	221.055	129.081

Table 2

	Demonstration CPPP		Advanced CPPP	
Agency	Undiscounted ($ millions)	Discounted ($ millions)	Undiscounted ($ millions)	Discounted ($ millions)
Army (Missiles)	1.463	.627	1.974	.801
Army	7.065	3.027	9.526	3.863
Department of Defense	39.147	16.773	52.785	21.404

Table 4

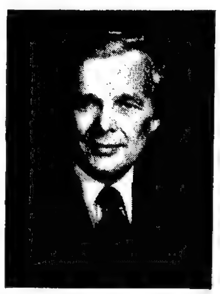
Savings Not Immediate

In all probability, the useful life of CPPP (or equally capable systems) will extend well beyond the 1980's. Major manufacturing systems which apply state of the art technology are not replaced every few years by the typical company. Instead, they are incrementally improved as additional technology is proven useful. Furthermore, the replacement of multiuser systems occurs gradually, as did their adoption. It is therefore felt that, with effective support, the benefits of CPPP in defense procurement would continue well after the 1987 limit.

The analysis suggests that CPPP has a large cost reduction potential in defense procurement. Savings of several millions per year are projected after full implementation is achieved. Greater industry acceptance would increase savings. Government activities which would enhance CPPP capabilities and/or reduce implementation effort could increase acceptance as well as increasing the savings realized by companies using the system.

Selections Tailored to Needs

NC Lathe Systems Evaluated



PETER D. SENKIW is President and a founder of Advanced Computer Systems, Inc., (ACS), where he has directed the firm's activities in the area of manufacturing systems. He has provided consulting and systems engineering support services to a variety of clients in many fields of computerized manufacturing including numerical control, direct numerical control, quality control and inspection, process control, automated testing, computer aided design and manufacturing, shop floor information control, data collection and acquisition, and inventory control. Mr. Senkiw has served as Project Contract Officer and Principle Investigator on two major numerical control language investigations for the Department of Army. One evaluated seven numerical control languages dealing with nonturning applications, and the second evaluated fifteen numerical control languages as they applied to turning operations. Prior to founding ACS, Mr. Senkiw was Manager of the Numerical Control Software division of National Cash Register, after several years as Manager of Data Corporation's Numerical Control and Computer Aided Design division. He also gained extensive experience in multiaxis NC gauge design while at Bendix Research and Development Laboratory and in electronics projects whiloe with the U. S. Air Force Foreign Technology Division and also Sylvania Electric Products Research Laboratory. Mr. Senkiw attended Ohio State University and Wright State University, where he received his degree in mathematics. He has completed graduate level courses in mathematics and computer science. He has held national and local offices in the Numerical Control Society as a member of the Board of Directors, Vice-President, and President. He is currently Chairman of the Long Range Planning Committee.

aced with the need to increase the productivity and reliability of turning operations in your shop? If so, you will probably be adding numerical control tools or seeking to improve control of those you already have. And that means you are probably in the market for a new numerical control lathe programming system and may be asking: "What is the best NC lathe programming system available?" That's a question you probably won't find an answer for—there are many systems available, each with its own set of advantages and disadvantages depending on the application.

But rephrase the question—"What is the best NC lathe programming system for my company for the next ten (or whatever number) years?"—and a useful answer becomes much easier. Now you can analyze the strengths and weaknesses of various available systems in light of your own capabilities and needs—if you have the necessary information and the know-how to use it.

Systems Report Available

A recent study by Advanced Computer Systems, Incorporated, for the U. S. Army Communications Research and Development Command (CORADCOM) provides help in that regard. The final report* on that study outlines an approach designed to help the potential user make the best choice for his unique requirements. An objective and quite extensive analysis of fifteen available languages and processes for programming NC lathes highlights this report. It reviews the capabilities and limitations of these systems, compares claimed and demonstrated performances of each, and discusses significant criteria to consider in comparing one system with another. It also addresses the assessment of your internal environment—capabilities, equipment, production mixes, for example—as it impacts NC lathe requirements. In their evaluation, Advanced Computer Systems made no attempt to rank available systems. What they have done is develop data and a methodology that will help you pick the system best suited to your needs.

Assessing Your Needs

Selecting a language and programming system involves a two part assessment. First, you must assess your internal environment. Then you can evaluate available systems to see which best matches the profile you develop. Advanced Systems has suggested a method of internal assessment that will provide a thorough, comprehensive, honest analysis of your situation.

Such an evaluation normally will be the responsibility of the Manager of Manufacturing Engineering, who

- Should have, or have access to, the necessary data
- Should be well equipped to appreciate the significance of the many factors to be considered
- Heads the department on which the programming task will fall.

The first step in internal assessment is determining the product mix—the ratio of parts turned on a lathe (1) to those shaped by milling, drilling, or boring machines, (2) to those made in a sheet metal punch, and (3) to all the other parts. Some parts require operations on both mills and lathes, but one characteristic usually predominates that will determine the classification.

The product mix is easily determined where some system of classification and coding (group technology) is used. In other cases, a sample group of drawings may be very quickly sorted into four stacks—lathe parts, milled parts, punched sheet metal parts, and others. The latter category covers purchased components, hardware, piping, springs, etc. Where there is doubt, the operations sheet for the part will help.

Precise figures are not necessary for this step, which merely is intended to show where most NC candidate parts are run—lathe or mill—and whether these ratios are likely to hold in the future. In many instances, the Manager of Manufacturing may be well aware of the ratios without a formal survey.

The product of this step is a simple matrix expressed in terms of the percent of total part designs (not manufacturing volume):

PRODUCT MIX

Type	% of Total	% Amenable to NC
Lathe parts		
Mill/drill/bore parts		
Sheet metal punched parts		
Other parts		

Volume Forecast

The next step in internal assessment is generation of volume forecasts covering the foreseeable future—realistically about five years. The Marketing Division can be asked for production volume trends and the Research and Development Division for probable new product introduction rates. Normally, this type of information is supplied regularly to the Manager of Manufacturing for his long range planning.

The result of the volume forecast, combined with that of the product mix forecast, will indicate the number of parts that must be programmed per year—or per month—and the trend of that number over the forecast period. A suggested format:

Volume Forecast

	5 years ago	Last year	This year	5 years ahead
New part designs				
New parts to be programmed				
Old parts to be reprogrammed				

Using this forecast, you can convert the number of parts to be programmed into approximate hours of programming time. To do this, take a representative sample of your lathe parts and examine a print of each. Then sort these parts into several categories based on programming difficulty, expressed as programming hours needed to get a usable tape. Ten categories at one hour intervals up to ten hours are sufficient. Advanced Computer Systems prepared estimates of programming time for different part categories and for the systems evaluated. These are shown in Table 1. (The companies and systems indicated by abbreviations at the top of each column are listed toward the end of this article.) This step yields a profile of the number of parts to be programmed versus their complexity, and, by multiplication, annual expected programming hours for any selected programming system.

Equipment Forecast

The third step in the assessment is to list NC equipment in your plant plus planned acquisitions. This list will include both NC machine tools and their adjuncts and also computers and their peripherals. The listing should cover a five year future, although the figures may change subsequently if the result of your assessment justifies the addition of more or different computers or more machine tools.

The result of the equipment forecast—combined with the volume forecast—will indicate when the computer system will reach its capacity and will have to be augmented; or, alternatively, when the volume of remote processing of programs will justify an in-house computing facility.

Part Character Forecast

As the final step in internal assessment, one should consider the evolution of part design complexity. It is common to find that as NC manufacture continues, more sophisticated parts are designed and a greater number of parts in a product are intentionally designed to take advantage of NC production. The result is a steady rise in the programming load, even though the volume forecast may show no growth.

Language and Programmer Assessment

In conjunction with the internal assessment, you also need to evaluate program language choices and available programmer skill levels. NC programming languages are what are known as "application oriented". Both man readable and machine readable, they must be man written. Their vocabulary, syntax, and structure are designed to describe the function they are to deal with rather than the way the computer is to deal with it. Because of the special characteristics involved, the programming language for lathe work may be simpler and less extensive than that used for milling work.

A special language will contain no more words than are necessary to describe the operations for which it was designed. The simpler the operations to be programmed, the simpler and smaller the processor will be. And the simpler and smaller the processor, the smaller the computer required (or, the faster a program will run in a given computer). This is particularly true in systems dedicated to lathe work.

Some systems can operate with two or three levels of a language. Simple lathe parts may be programmed using a subset of the language of limited scope; more complex parts may be programmed using a larger subset of the language, with a more complex syntax; the most complicated parts may require the full capabilities of the parent language. The system's processor will accept input on any level, and the levels usually can be mixed together in one program. The range of use required for your particular product mix will have to be determined.

Three Dimensional Visualization Required

The total product mix will also affect the type of language selected. The NC programming department will have to program whatever parts are designed. Generally, it is desirable to have as few different NC systems as possible in use at any one time. This is to avoid confusion, reduce computer hardware and software requirements, and increase the flexibility of part programmers' work assignments. There are three possible avenues:

- One system, capable of handling all NC tools in the plant
- Two systems, one for lathes and one for machining centers
- One computerized system for the dominant type of tool installed—lathes or mills—plus manual programming for the few remaining tools if the computerized system will not handle them as well.

The choice may be clearly dictated by the product mix or may have to be resolved by an economic balance.

To help minimize errors, a single language for all NC equipment in a plant is desirable. Regardless of the language or languages chosen, programmers' ability to produce efficiently will depend on two skill factors:

- Their experience in writing programs in a given language
- Their native ability to visualize three dimensional machining processes from a two dimensional drawing.

In assessing programmer skill level, remember that time will enhance the first skill, but conceptualization is innate—one either has it or not. Also, the volume of work justifies only one programmer, but that person must be capable of handling any part that is designed in the plant. But, where there is a large volume of work, you can manage whatever spread of talent is available and required to best meet demands of various designs.

System Selection

In summary, the internal assessment will describe

- Product mix—lathe/mill/punch/other parts
- Volume forecast—new parts programming and support reprogramming
- Equipment forecast—computers and NC tools
- Part characteristic forecast—complexity trend
- Options in language choice—full range vs limited application; one, two, or more languages
- Programmer skill levels available.

With the assessment complete, the trick is to match the internal (demand) environment with the external (supply) environment.

The first question to ask is which available systems have the technical capacities to match your five year characteristic profile. Then you need to estimate the cost of the possible alternatives. The programming volume forecast will tell roughly how many programmers will be needed; this in turn suggests the number of terminals that will be needed.

This approach should clearly indicate what kind of a system is needed and which systems should be considered further. At least the list of possibles should be cut to two or three.

Contemporary Information Necessary

At this point, interviews with system vendors are in order. While the data supplied in the CORADCOM report is accurate when assembled, it may well have changed by the time a potential user applies the data. NC programming systems are in a constant state of improvement and enhancement. Thus, the CORADCOM data—on both capabilities and costs—may be useful in initial assessments but certainly should not be relied on for final decisions.

Since selection of a programming system is a relatively long range commitment, you will be entering a close association with the system vendor. Check with other users to examine the vendor's reputation and experience with the equipment. Ask the vendor probing questions regarding experience and services. In short, decide whether or not you will feel comfortable and secure with this vendor.

With this type of selection study, the mysteries of choosing a system will be less puzzling and the hazards reduced. The ultimate choice will stand partly on objective factors and partly on subjective judgment and must after all, be made by the potential user.

Study Data Helps

Nonetheless, (remembering the caveats expressed above), the analysis and data prepared for CORADCOM by Advanced Computer Systems should prove very useful in guiding your decision. The reported examination of fifteen systems is quite comprehensive and objectively presented.

To initiate this examination, the contractor prepared a list of twenty-nine companies that were reported to have an NC lathe system available. Invitations to participate in the study were mailed by the contractor to all of these companies, but there was no pressure put on participants. After lengthy negotiations and elimination of those systems that were not commercially available or not currently supported by the supplier, the following fifteen systems and proponents were selected for examination:

Cinturn II	Cincinnati Milacron, Inc.
QUICK-PATH	Digital Systems Corp.
Genesis	Encode, Inc.
GETURN	General Electric Co.
Ingersoll Lathe Prog.	Ingersoll Milling Machine Co.
COMPACT II	Manufacturing Data Systems, Inc.
TOOLPATH	Manufacturing Software and Services
APT for Lathes	McDonnell Douglas Automation Co.
GTL/T	Olivetti Corp. of America
APTURN	Structural Dynamics Research Corp.
VNC	Threshold Technology, Inc.
UNIAPT	United Computing Corporation
UCCAPT	University Computing Co.
PROMPT	Weber NC Systems
WESTURN	Westinghouse Electric Corp.

Each company agreed to participate and to cooperate with the contractor to the extent necessary. Their participation included furnishing documentation and information and demonstrating their system on test patterns and test parts.

Basically, the examination covered the following areas:

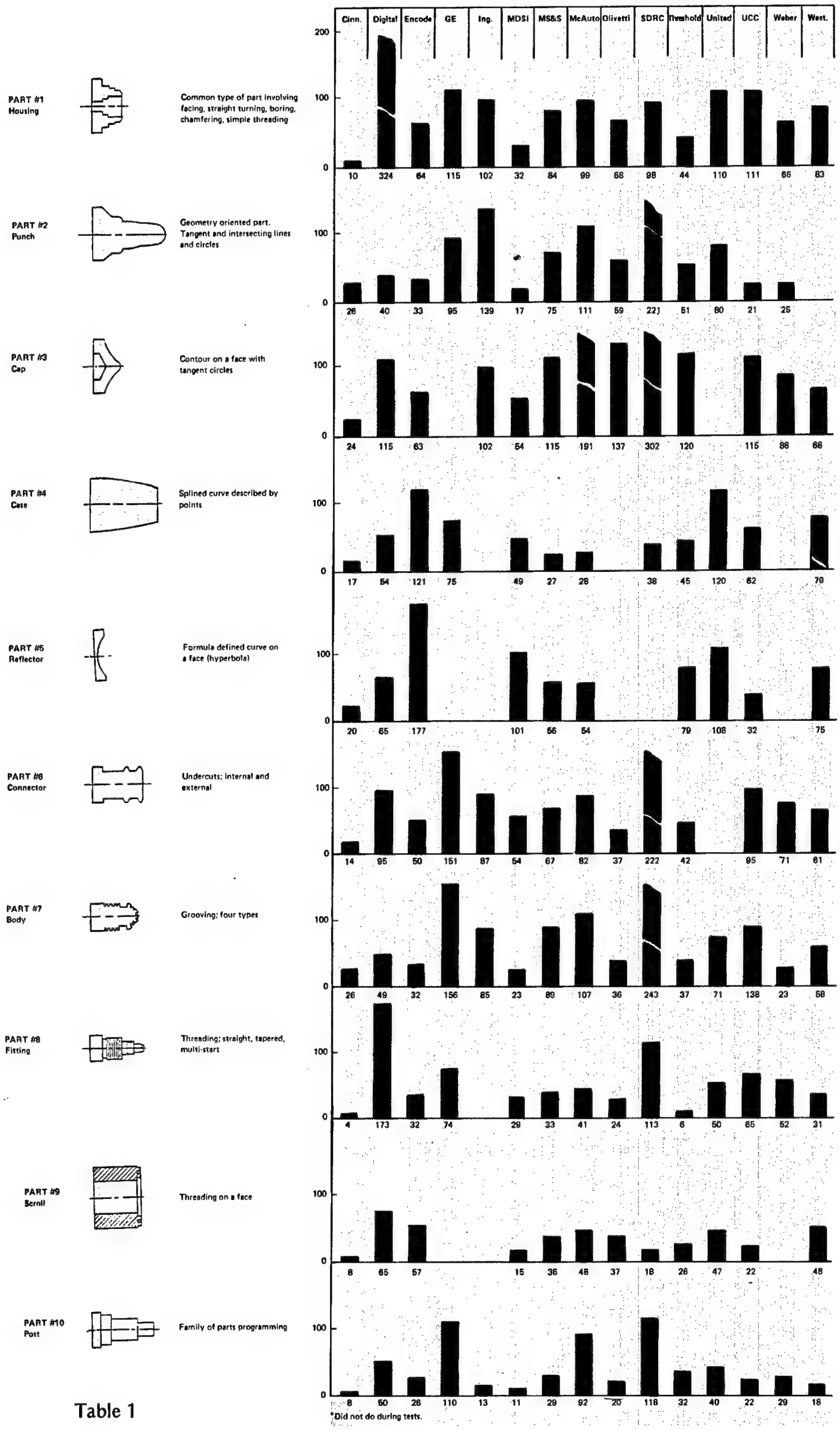
- Basic geometrical capabilities
- Lathe programming routines
- Distinguishing characteristics
- Response to test patterns and to benchmark tests.

Report An Invaluable Tool

In summarizing the examination of these systems, the CORADCOM report

- Describes the nontechnical characteristics of each system—hardware and software sources and costs, documentation, training, vendor support, and maintenance.
- Tabulates the capabilities of the languages in describing the geometrical configurations of the part being programmed and the variety of the geometrical formats accepted.
- Discusses the use of macros to simplify the writing of programs to perform the common operations of all lathe work.
- Presents a brief discussion of the distinguishing characteristics of each system.
- Describes the preparation of the ten test parts used in demonstrating the capabilities of the systems.
- Describes the capabilities demonstrated by each system to program the ten test parts.
- Gives the time required to write and debug the program on each system.
- Discusses the success of each system in processing and postprocessing the programs.
- Presents cost data on running programs on the various systems.

It provides an invaluable tool for a company considering an upgrade of its NC lathe capabilities.



Part	Description	Cinn.	Digital	Encode	GE	Ing.	MDSI	MS&S	McAuto	Olivetti	SDRC	Threshold	United	UCC	Weber	West.
PART #1 Housing	Common type of part involving facing, straight turning, boring, chamfering, simple threading	10	324	64	115	102	32	84	99	68	98	44	110	111	66	83
PART #2 Punch	Geometry oriented part. Tangent and intersecting lines and circles	26	40	33	95	139	17	75	111	59	221	51	80	21	25	
PART #3 Cap	Contour on a face with tangent circles	24	115	63		102	54	115	191	137	302	120		115	88	68
PART #4 Case	Splined curve described by points	17	54	121	75		49	27	28		38	45	120	62		79
PART #5 Reflector	Formula defined curve on a face (hyperbola)	20	65	177			101	56	54			79	108	32		75
PART #6 Connector	Undercuts; internal and external	14	95	50	151	87	54	67	82	37	222	42		95	71	61
PART #7 Body	Grooving; four types	26	49	32	156	85	23	89	107	36	243	37	71	138	23	58
PART #8 Fitting	Threading; straight, tapered, multi-start	4	173	32	74		29	33	41	24	113	6	50	65	52	31
PART #9 Scroll	Threading on a face	8	65	57			15	36	48	37	18	26	47	22		48
PART #10 Post	Family of parts programming	8	50	26	110	13	11	29	92	20	118	32	40	22	29	18

*Did not do during tests.

Table 1

Features Improved Cooling

Turbine Blade Redesign Boosts Life

A 50 percent decrease in manufacturing costs and increased service life have been the prime benefits resulting from a small turbine blade advancement study by the General Electric Company's Aircraft Engine Group in Lynn, Massachusetts.

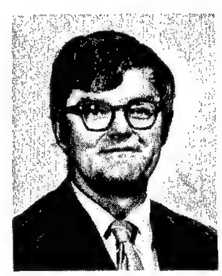
The twin objectives of the study were to (1) develop coring techniques to minimize machining, improve producubility, and reduce the cost of the T700 Stage 2 turbine blade and (2) develop an advanced core technology for small air cooled turbine blades applicable to the T700 Stage 1 turbine blade.

All of the advanced gas turbine aircraft engines developed by the G.E. Aircraft Engine Group use highly alloyed, gamma prime strengthened superalloys for the hot rotating turbine components. The alloys of particular interest for equiaxed turbine blades within G.E. are Rene' 80, Rene' 120, and Rene' 125. While these alloys offer remarkable properties at elevated temperatures, the requirements of long blade life, lower fuel consumption, and lower manufacturing cost demand that the gas turbine blades be cooled by various advanced techniques.

Best Quartz Rods Used

The usual practice is to provide internal cooling passages through the use of casting techniques. In the case of thin blades and small hole sizes, cast cooling passages are supplemented with machined cooling holes. The machining characteristics of the Rene' superalloys—coupled with the high length to diameter ratios of the cooling passages—require heavy dependence upon unconventional machining methods such as Electrical Discharge Machining (EDM), electrostream, Shaped Tube Electrolytic Machining (STEM), and laser drilling. These sophisticated operations result in higher costs than are involved in cored passages alone.

The cooling passage casting techniques developed over the past few years for large thin walled turbine blades have relied upon single piece injection molded ceramic core bodies with intricate cooling features such as turbulating bumps, serpentine passages, and oval trailing edge chordwise bleed holes. Small cooled turbine blades, on the other hand, have been constrained by the state of the art in ceramic core technology, which has limited the core sizes and configurations available to the design



G. STEELE IRONS is a specialist in casting technology at General Electric's Technical Resources Operation, Aircraft Engine Group, Lynn, Massachusetts. Prior to joining General Electric in 1972, Mr. Irons' experience involved Government contract research in welding, casting, and powder metallurgy. At General Electric, he has worked in casting technology, initially with structural components and most recently in the specialized area of turbine airfoils. He was Principal Investigator on two U. S. Army funded blade technology programs which have resulted in direct production application of the developed technologies. He is the Technical Program Manager of an Air Force funded program which is investigating suitable processes for directional solidification of small air cooled turbine blades. Mr. Irons' current position at G.E. is Manager of Precision Casting Technology, where he has responsibility for all small engine castings ranging from advanced design concepts to technical support for internal operations as well as vendor supplied castings.

engineer. An important practical solution to this problem has involved the use of bent quartz rods to obtain small diameter radial convection cooling passages unobtainable with ceramic cores. However, the shapes of these passages have been limited to uniform cross sections extruded as hollow or solid rods. Special machining techniques were developed during the course of the program to produce turbulators on the leading edge quartz core and to provide the conical trailing edge quartz core. In addition, improved bending methods were evolved to avoid significant stretching of the bent areas in serpentine quartz rods used as mid-chord cores.

Stage 2 Blade Costs Reduced

The original T700 Stage 2 blade design specified four radial cored cooling holes, six drilled chordwise trailing edge cooling holes, and a cast-in tip plenum cavity as shown in Figure 1. This design required a brazed cross pin to close the radial hole at the stepped section near the plenum cavity. It was found that the drilled trailing edge holes and the cross pin closure represented significant manufacturing cost elements. Accordingly, plans were made to reduce the cost of the Stage 2 blade by selecting a configuration with six radial holes spaced out to cool the blade cross section as shown in Figure 2. This one

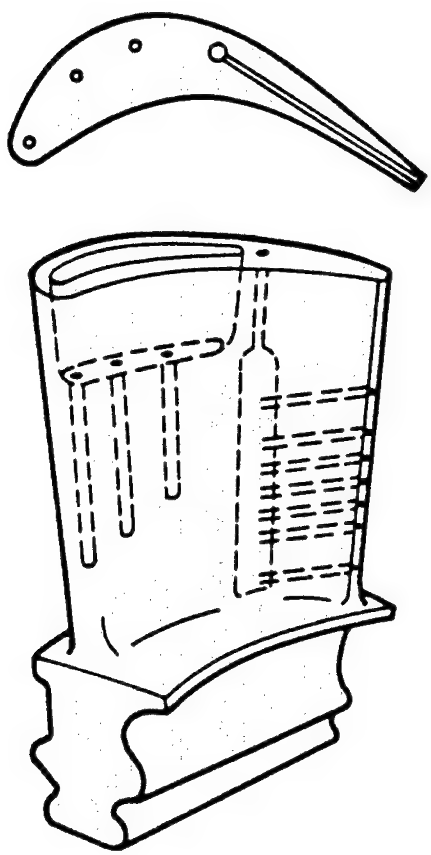


Figure 1

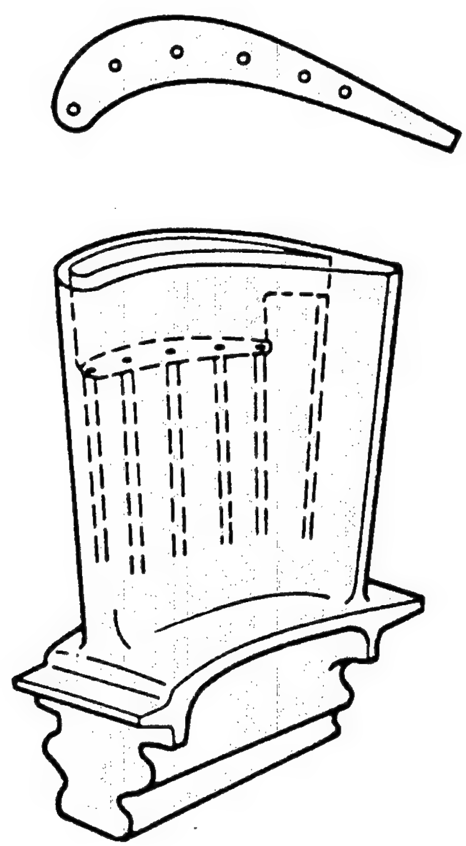


Figure 2

step casting approach involved the use of quartz rods to form the radial cooling passages and the use of EDM to form the tip plenum cavity.

The material selected for the Stage 2 blade was Rene' 125, a highly alloyed gamma prime strengthened nickel base superalloy. This alloy was developed by General Electric for use in all engine lines. It has a balanced/optimized composition with the addition of hafnium to improve castability over the previously used Rene' 120 material. The principal advantage of Rene' 125 is that its increased grain boundary strength minimizes hot tearing in the thin wall areas associated with cored holes.

Stage 1 Blade Redesigned

The original T700 Stage 1 blade design specified eight radial cooling holes. Seven of the holes were round, including six stepped mid-chord holes, while the trailing edge hole was oval. An improved production configuration involved the addition of a mid-chord hole, elimination of the stepped mid-chord cores, and substitution of the oval trailing edge hole with a conical hole placed closer to the trailing edge.

In the case of the advanced Stage 1 blade design,the decision was made to exploit advanced coring technology to improve cooling air effectiveness and to reduce manufacturing cost. Therefore, the following changes were made in the Stage 1 blade design:

- Turbulated leading edge oval hole
- Two serpentine shaped mid-chord holes.

Figure 3 shows a schematic of the new Stage 1 blade design. The design includes provision for small dust bleed holes at three locations at the blade tip: the tops of the serpentine passages and the tip of the conical plenum. This feature is particularly important in the case of the serpentine passages since engine operation in dusty environments could otherwise result in blockage of these passages at the bends. The material selected for the Stage 1 blade was Rene' 125.

Stage 2 Blade Heat Transfer

A computerized heat transfer analysis was performed on the Stage 2 blade based on the following requirements:

- No change in performance over chordwise cooled design
- No change in outer airfoil configuration
- Same cooling airflow as chordwise cooled design
- Same maximum turbine inlet temperature.

The heat transfer analysis revealed that the trailing edge temperatures in the radial hole design were somewhat higher than those in the chordwise trailing edge hole design. This produced a bulk temperature for the radial blade that was 11 F above that of the chordwise trailing edge blade. However, due to the lower design stress for the radial blade—as well as elimination of the stress concentration factor associated with the trailing edge holes—the stress rupture life was not reduced by the higher bulk temperature of the radial blade. This later was substantiated by engine tests wherein the radial hole design showed a significant improvement in life over the chordwise trailing edge hole design.

Stage 1 Blade Analyzed

The requirements for the heat transfer analysis for the Stage 1 blade were as follows:

- No change in aerodynamics over production design
- No change in outer airfoil and shank configuration
- Same maximum turbine inlet temperature.

The operating conditions set for the thermal analysis were rated power, with 30 F margin added to the turbine inlet temperature. It was found that the temperature

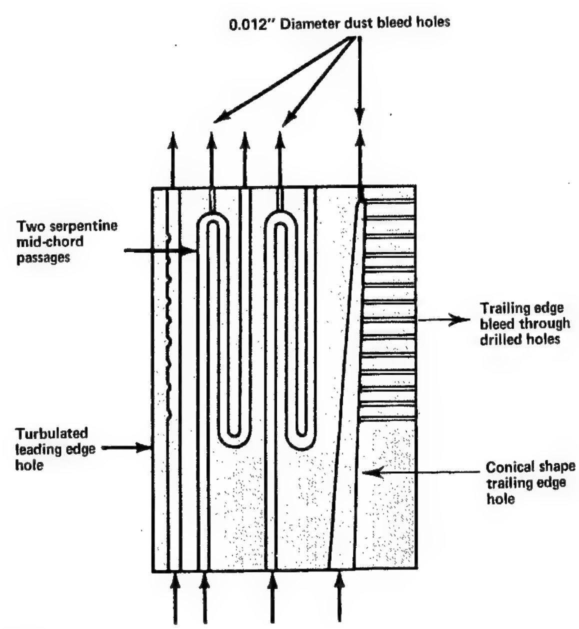


Figure 3

ceramic core for the conical trailing edge air passage. Although the main core was produced successfully, yield problems developed with excessive breakage of the small diameter dust hole core. Therefore, it was necessary to resort to conventional machining of quartz to produce the conical trailing edge core. The dust hole at the top of the conical air passage was produced by welding a small diameter quartz tube to the machined quartz rod.

Both the T700 production and the advanced core technology first stage high pressure blades utilized precision investment casting techniques. Two areas of concern from the casting standpoint were relative to the serpentine mid-chord holes. These were (1) the tendency of S-bends to distort and produce a thin wall condition and (2) possible difficulties in leaching the quartz material from the S-bend passage. Neither condition presented a problem.

Stage 2 Blade Qualified

Extensive qualification tests were performed on the Stage 2 blade to qualify it for use in the T700 engine. Airfoil fatigue strengths of the radial hole blades were determined in the first flexural mode with the dovetail tightly clamped. All blades tested were finish machined and the airfoils coated with an aluminum vapor designed to protect the blade from hot corrosion in service. Twelve blades were tested—six in Rene' 125 material and six in Rene' 120. Table 1 summarizes this data.

For the Rene' 125 radial hole design, the average 10 million cycle fatigue strength was 58,000 psi. Previous tests on the chordwise trailing edge hole design showed a fatigue strength of 40,000 psi for Rene' 120 material. Thus, the radial hole design represents an improvement of about 18 ksi. As shown in Table 1, the radial hole blade in Rene'120 material has a fatigue strength of 59,000 psi.

Configuration	Material	Fatigue Strength, ksi
Trailing Edge	René 80	40
Trailing Edge	René 120	38
Radial Hole	René 125	58
Radial Hole	René 120	59

Table 1

Thus, it can be stated that the improvement in blade fatigue life was due entirely to the change in design approach and not to the change in material.

Frequency distribution and nodal patterns were determined for two of the radial hole Rene' 125 blades. A search was made for resonant frequencies for all modes below 30,000 Hz. There was no evidence of airfoil resonance within this range at normal engine operating frequencies.

A series of three 150 hour engine endurance tests was accomplished successfully with the radial hole blade. This blade design was qualified for use in the T700 engine on the basis of these tests as well as the above bench fatigue tests and metallographic examinations.

Advanced Core Blade Acceptable

The advanced core technology blade was proven acceptable for use in the T700 engine on the basis of adherence to the applicable engineering drawings and its similarity to previously tested designs.

Since the high cycle fatigue strength of the Rene'125 alloy had been adequately established on this and other configurations, no fatigue tests were necessary on the advanced core technology blade. Metallographic inspection of airfoil and shank sections showed the blade to be sound and essentially free of microshrinkage. In addition, radiographic and surface penetrant inspections did not reveal any defect in the castings or finished machined parts.

Significant Cost Savings

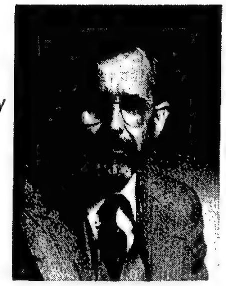
On the Stage 2 blade, the cost savings were 10.5 percent of the original design 1974 manufacturing cost for production quantities.

In the case of the Stage 1 blade, cost estimates indicated that small molded ceramic cores can be produced for about 50 percent of the cost associated with similar shapes machined from quartz rods.

The results achieved during the course of the Stage 2 blade improvement program are summarized below:

• No trailing edge cooling holes	25 Percent stress reduction
• Retilted airfoil	10 Percent stress reduction
• Use of Rene' 125 material	25 Percent life improvement
• Airfoil fatigue (room temperature)	50 Percent improvement
• Trailing edge temperature	Higher by 90 F
• Engine life	Greater than 20X
• Casting process yield	20 to 85 Percent
• Cost reduction	$527 (1980) Per engine set

DR. ARTHUR G. METCALFE is co-inventor with Fred K. Rose of the isothermal rolling and roll forge processes. He was born in England and educated at Cambridge University He has been with Solar Turbines International since 1959, where he is Associate Director of Research. Burton G. Bailen joined Mr. Rose and Dr. Metcalfe recently to advance these processes into production.



Isothermal Rolling of Aircraft Parts

Versatile Process Saves Costly Materials

Material utilization continues to be a key factor in controlling manufacturing costs as material prices steadily increase. Isothermal rolling is one of several emerging forging processes that show great promise for reducing the excess material required for machining parts from conventional forgings and extrusions. For example, longerons for the F-18 now require 250 pounds of starting material to produce aircraft sets that weigh just 61.6 pounds. But the blank for isothermal rolling of these parts would weigh only 76 pounds, a savings of 174 pounds of material per aircraft. Based on this, estimated dollar savings in material and reduced machining time are $4,000 per aircraft. This is only one of many potential aircraft applications for this process, which can be modified to meet different needs.

Isothermal rolling uses molybdenum alloy rollers which shape the metal while also serving as electrodes to provide local electrical resistance heating. The basic principle is illustrated in Figure 1. The current (I) heats the workpiece and enough of the roll to form a travelling hot zone. Shaping occurs under the combined action of the squeeze force (F) and a feed force (FF). The feed force is essential for large reductions that may exceed 95 percent in a single pass. Without force feeding, roll slippage occurs and very little reduction per pass is obtained.

The process is very versatile and can be modified for various configurations. Variations include one roll operating against fixed tooling, the use of shaped rolls, the use of split rolls, the use of roll forge dies, and combinations of these. Four programs at Solar Turbine International to develop isothermal forging for aircraft parts illustrate the versatility of the process.

ROLL FORGED COMPRESSOR BLADES

In an Army sponsored program, Solar is developing isothermal roll forging of the T55 second stage compressor blade shown in Figure 2. This blade is forged from AM 350 alloy. Isothermal roll forging offers major cost reduction potential by shaping bar stock to the blade configuration in a continuous operation controlled by microprocessors. The root is formed by programmed upsetting followed by transition into airfoil rolling. A separate stress relief operation includes setting of blade twist.

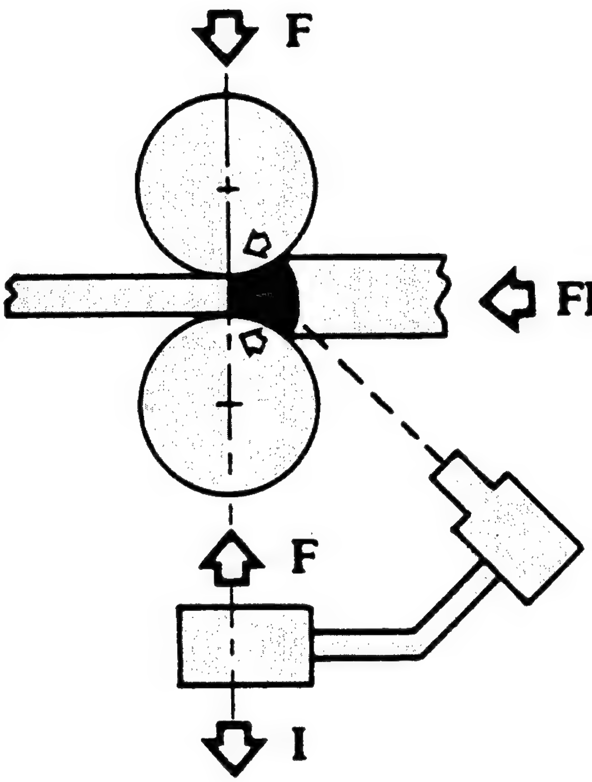


Figure 1

In the first phase of this program, feasibilit,· of blade manufacture was demonstrated, with blades manufactured to within a tolerance of 0.010 inch. In the second phase, dimensional control was tightened using an improved manufacturing process in a special machine of the knuckle rolling type.

The method used in Phase I is illustrated in Figure 3. It includes two operations—root injection and airfoil rolling. For root injection, the required die shape is sunk into the roll surface. The rolls are synchronized and clamped on the bar at the blade root position. Die squeeze and heating current are increased until the forging temperature is reached, at which time feed force is applied to the end of the bar until it upsets to fill the root pocket. A constant forging temperature is ensured by optical pyrometer sighting on the bar. The forging temperature is attained in about 30 seconds and root injection takes another 15 to 20 seconds. Root injection parameters for the AM 350 blade were 10,000 lb force and 2050 F.

To roll the airfoil, a tip feed force is used to ensure spreading to the full blade width, with tension applied to the root to maintain airfoil straightness. Airfoil shape is controlled largely by the accuracy of die sinking. The thickness is governed by the die gap setting and other factors. It was concluded from this work that more accurate die setting was a key requirement. During the program, as rolled forged dimensions well within the program goals of 0.010 inch were obtained.

Phase II of the Solar program was conducted in a much stiffer machine with 100,000 pound squeeze capability and segmented dies rather than rolls. The root force feed on this machine is provided by a cylinder and die set at the top with a similar set below the machine providing the tip feed force. The machine is equipped with a microprocessor which controls each individual process and makes the transition from one process to another so that the isothermal roll forging can be performed in a single operation.

At the present time, the blades require a finish roll forging pass for gage control. A hot press forging operation is used to impart twist and provide stress relief. The first batch of AM 350 blades formed on this machine showed improved thickness control, but further iterations of the roll forging process are needed to obtain optimum control.

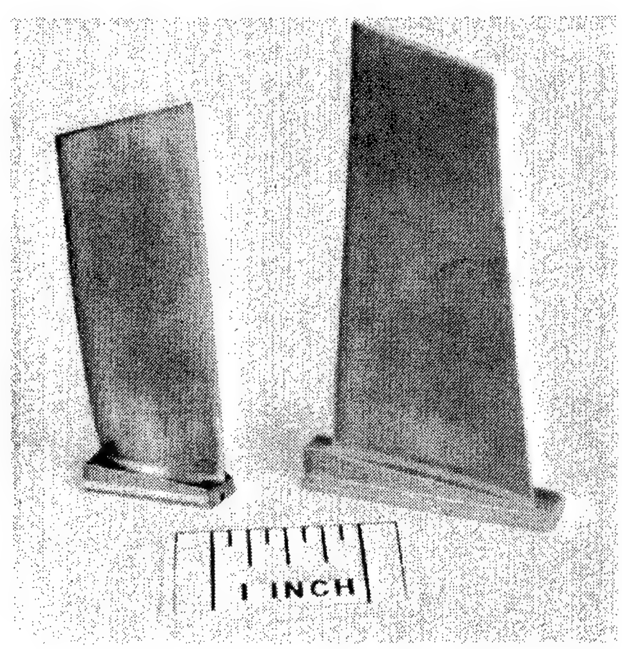


Figure 2

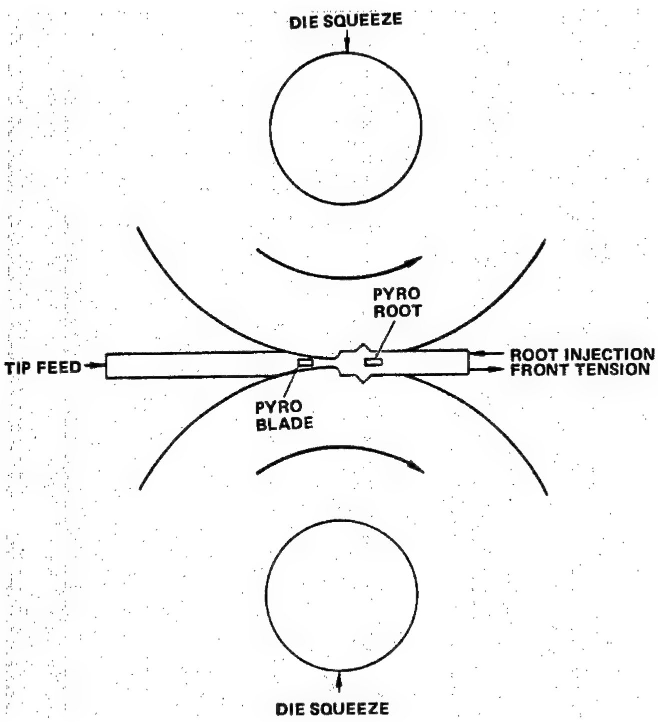


Figure 3

Metallurgically, roll forging at 1950 F with this machine allows good control of ferrite in the AM 350 alloy. Tensile properties are well above minimum specifications for T55 blades. The process should provide substantial cost savings by

- Reducing the number of operations
- Process automation through the microprocessor
- Roll forging of thin trailing edges.

RING ROLLING

Aircraft engine rings are made from high strength, difficult to shape alloys—especially titanium alloys. Because of the difficulty encountered in shaping them, heavy ring forgings or flash butt welded bars are machined to the final shape with as little as 5 percent material utilization. With isothermal rolling of rolled and welded barstock, a net shape is obtained in a single pass. Hot expanding to size and edge trimming complete the processing.

Following a survey of candidate parts, Solar selected large flanges as most effective for demonstrating the ring rolling process. The first choice was a flange from the General Electric F-101 engine duct fan assembly. This 42 inch diameter, 5.2 lb ring presently is machined from a 50 pound blank. The potential savings in material costs and machining time are dramatic.

The setup for isothermal ring rolling is shown in Figures 4 and 5. Prior to rolling, ring blank pairs are processed by

- Selecting the blank size required
- Rolling the "hard" way to diameter
- Cutting the ends and welding
- Tack welding two blanks together
- Machining the shoulder on each side of the ring blank pair.

The blank size is calculated from the cross section of metal required and the diametral growth (if any) in isothermal rolling. Blank size for the ring selected was 0.375 by 1.50 inches. Electron beam welding was used to join the blanks.

For rolling, the ring blank is inserted into place on the machine and the jaws are set. To begin the shaping process, the squeeze force and current are gradually increased until a "foorprint" grows between the rolls. This footprint allows the full machine current (30,000 amps nominal) to be used at a rolling temperature of 1750 F. The force feed then is started and, as force builds up, the rolls are started. However, two roll passes were needed with the machine available.

Eight rings were rolled to demonstrate and refine the process. Typical parameters for the first pass were as follows:

Squeeze	35,000 lb
Feed	10,000 lb
Temperature	1750 F
Current	14,000 amps
Speed	1 ipm

The outer diameter changed by 0.024 to 0.082 inch for a ring of 42.6 inch diameter. This first pass generated flanges of 0.25 inch thickness and 1.4 inch width for the back to back pair of rings.

Typical parameters for the second pass were as follows:

Squeeze	40,000 lb
Feed	9,600 lb
Temperature	1745 F
Current	29,000 amps
Speed	1.5 ipm

After this second roll pass, the flange width was ap-

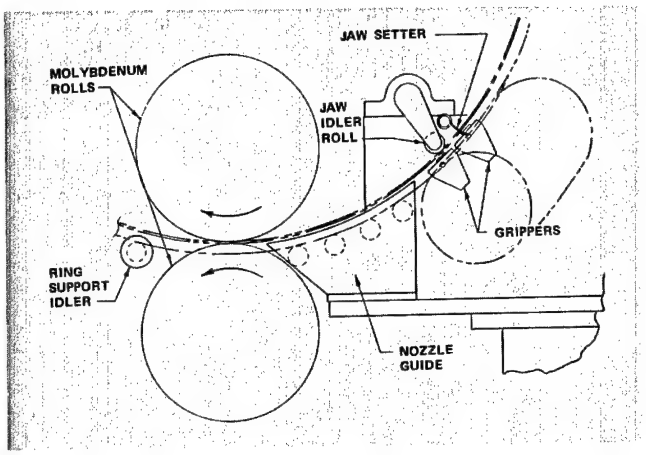


Figure 4

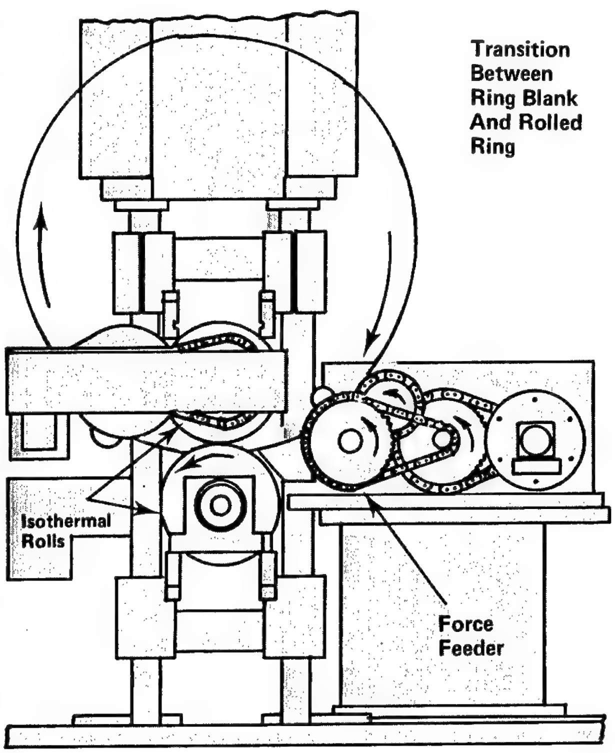


Figure 5

proximately 2.5 by 0.110 (±0.012) inches thick. This allowed adequate stock for trimming to width (2.2 inches required), but the variation in thickness was greater than the ±0.010 inch allowed. Variation in the feed force was responsible for this inconsistent thickness. Diameter growth of 0.09 to 0.18 inch was within the tolerance band allowed for the delta-alpha sizing method used. Final diameter was held within the ±0.020 inch permitted for this ring.

Analysis showed that 36 pounds of titanium alloy and $670 (1979 dollars) could be saved over the conventional method of manufacture from machined ring forgings.

CUSTOM FABRICATION OF T-SHAPES

The Navy's F-18 aircraft includes many titanium alloy stringers and longerons that are machined from heavy section extrusions. A large percentage of starting material is lost. Isothermal rolling will reduce the costs of these parts by producing net thickness T-sections, thereby eliminating the usual excess on all dimensions. With additional metal added by electron beam welding, a second rolling pass produces "custom" sections.

Figure 6 shows a longeron from the F-18 where the flange requirement of 4.54 inches at one location demands a 5 inch wide extrusion throughout. The estimated weight of this part per aircraft set is 61.6 pounds, but its manufacture requires 250 pounds of extrusion. As noted earlier, the blank for isothermal rolling will weigh just 76 pounds—a savings of 174 pounds—which translates into a savings of $4,400 on each aircraft.

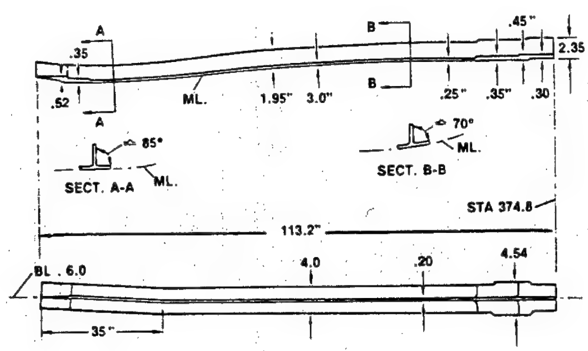


Figure 6

The basic method for rolling T-sections in Ti-6A1-4V uses two passes—stem rolling and flange rolling—as shown in Figure 7. Typical parameters for each pass are as follows:

	Stem Rolling	Flange Rolling
Squeeze force lb	40,000	48,000
Feed force lb	2,000	7,500
Current, amps	16,000	28,000
Speed, ipm	1.0	1.0

The T-sections are stress relief annealed and straightened at 1350 F to produce the T's shown in Figure 8.

Together with electron beam welding, the process can be used to make variable sections—custom T's—with flange thickening or widening or deeper webs.

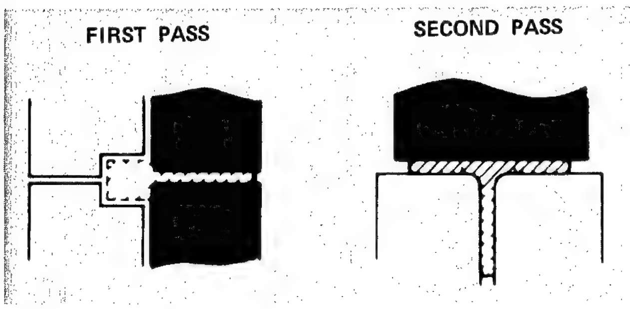


Figure 7

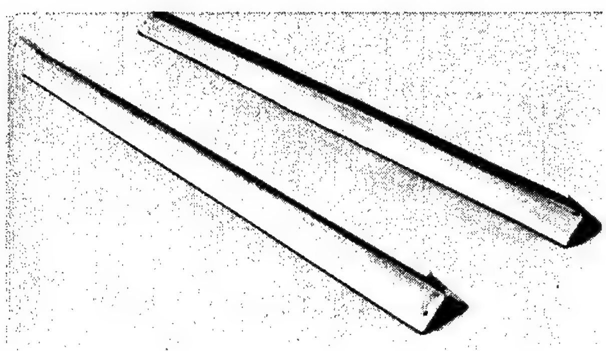


Figure 8

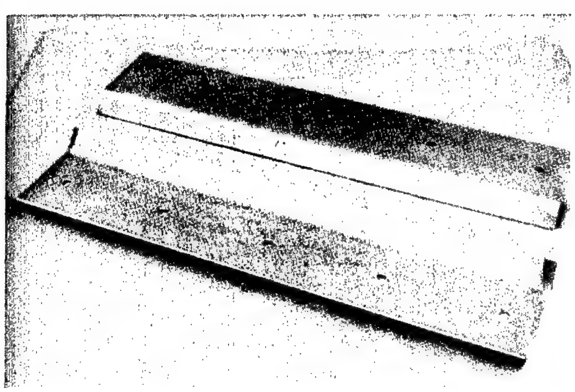


Figure 9

SQUARE BEND PROCESS

Also under Navy sponsorship, Solar is developing the SQUARE BEND process of isothermal rolling. Here, a radiused bend in sheet or plate is ironed by a roll to form a square external corner with a filleted internal corner.

Figure 9 shows brake formed parts in Ti-6-6-2 with an approximately 5t bend. These parts are clamped into simple tooling and rolled isothermally to produce the configuration shown in Figure 10.

An as rolled bend is shown in Figure 11. At the present time, two passes are required to obtain the full bend. Typical SQUARE BEND rolling parameters are 6,000 lb squeeze force, a 4500 amp current, and a speed of 3 inches/min.

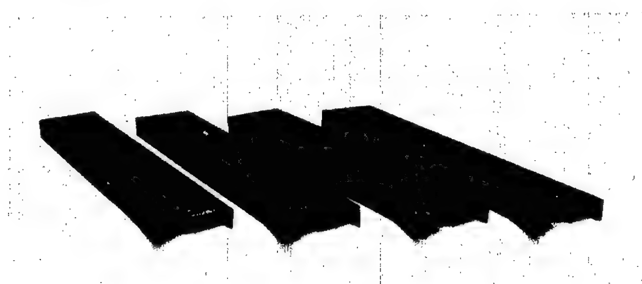


Figure 10

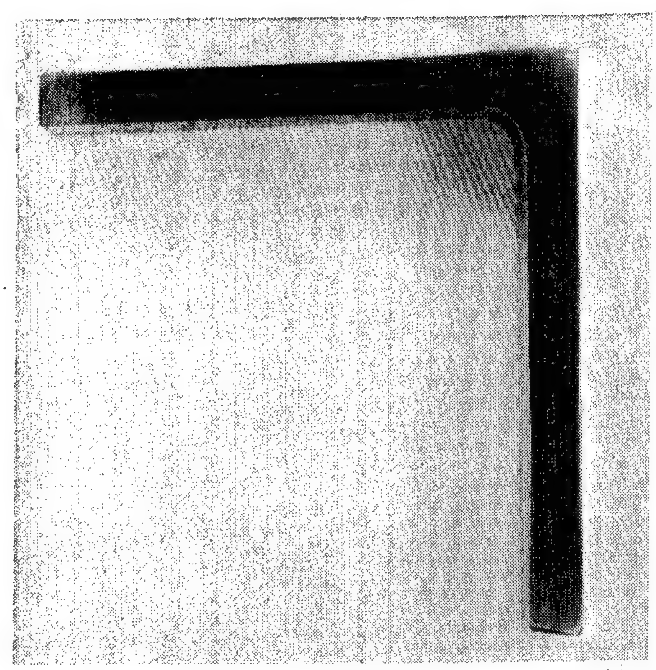


Figure 11

faces are separated by a distance between 1.02 and 1.15 times the barrel diameter.

Figure 2 shows a typical rifling mandrel used for radial forging, which, except for attachment, is similar to those used for swaging. A tapered mandrel is frequently used to minimize contact with the bore and to permit adjustment of the bore dimensions. The mandrel is located between the dies and freely rotates as the preform is forged over it to impart the rifling.

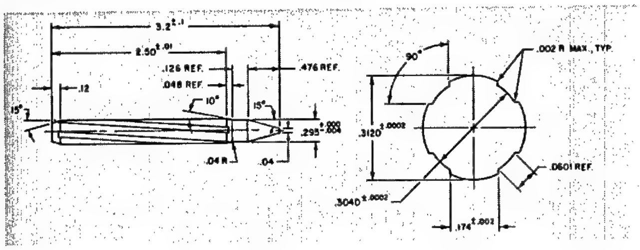


Figure 2

Radial Forging

GFM, of Steyr, Austria, manufactures the only radial forging machine for rifle barrels. Production machines normally have integral, fully automatic control (NC or template) and overload protection. Machines can also be purchased with automatic induction heating to heat the preform just as it enters the dies. Forging is accomplished by moving the rotating preform past four radially aligned dies or hammers. The preform is held on centers by a counter holder and chuckhead, which also provides the rotational motion at a preset speed.

Figure 3 is a schematic of combined rifling and chambering by rotational forging. It shows the positions of the hammers and mandrel at various points in the forging cycle relative to the preform and forged blank. The barrel is gripped and rotated by the chuckhead and forced against the counter holder at a preset back pressure. During the forging cycle, the hammers move continuously in and out through a small amplitude (a few millimeters depending on the machine size) for OD contouring. The hammers are driven by cams through the template or NC control.

Both the "guide bush" and the chuckhead contain hydraulic pistons (the counter holder and plunger, respectively) which contact the part. The plunger moves with the chuckhead during rifling to produce the preset counter holder pressure, similar to swaging. However, at a preset position near the required chamber area, the mandrel begins to move with the chuckhead as the chamber neck and shoulders are forged. The relative counter holder and plunger pressures then change, causing metal flow toward the breech and into the chamber contour. Continuous forward flow toward the nozzle would not produce complete chamber fill.

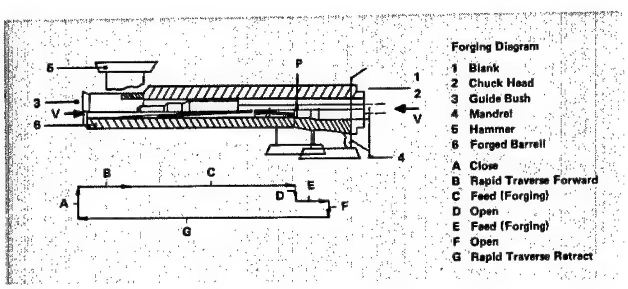


Figure 3

The die design recommended by GFM for combined rifling and chambering is shown in Figure 4. This design provides low forging loads, improved rifling and chamber quality, and successful forging of a wide variety of barrel diameters and contours. Different entrance angles on the opposing die halves produce a slight ovality that minimizes air entrapment during forging. This ovality is removed in the land area.

Figure 5 shows the template, forged barrel blank, machined preform, and heat treated (to Rc 36 to 38) rod preforms used to produce a cold forged M134 barrel in H11 material.

The recommended feed rate for radial forging of small caliber barrels is 100 mm/min (3.94 inches/min) for a hammer rate of 1000 blows/min. However, proprietary

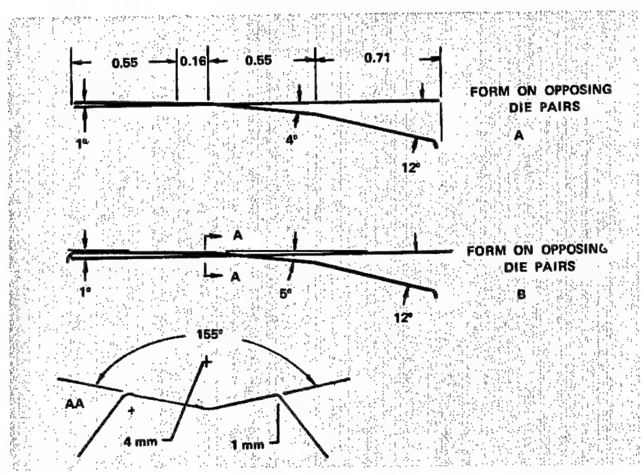


Figure 4

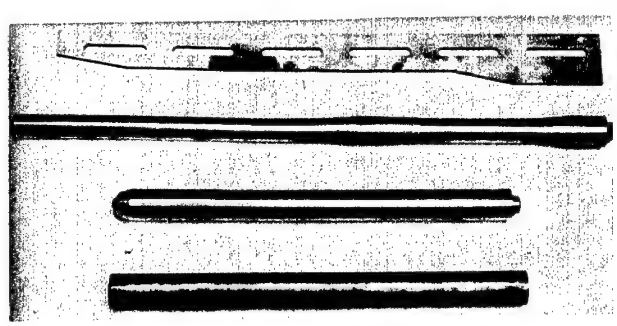


Figure 5

processes using three to four times this rate to produce an excellent product have been reported. Typical reductions are in the range of 18 to 25 percent for rifling and 22 to 35 percent for combined rifling and chambering.

Quality Considerations

Rotary forged barrels are typically very straight and precise. To effectively utilize this capability, materials are fully heat treated prior to forging. Bore accuracies reported by GFM for radial forging, and supported by production experience, are ±0.0025 mm for bores of up to 8 mm diameter, ±0.005 mm for bores up to 13 mm, and ±0.0075 mm for bores up to 20 mm. Similar accuracies can be obtained by swaging. Both radial forging and swaging can produce even greater accuracies with specially developed production tooling.

Material properties are an important consideration in obtaining precision forgings. The reduction capability of rotary forged materials appears to be controlled by the transverse properties, which are difficult to measure for the typical preform sizes. The most common type of gross failure is longitudinal splitting associated with gross microstructural inhomogeneities (i.e., stringers). For this reason, free machining steels are not recommended. However, all barrel materials contain both intentional and unintentional microstructural inhomogeneities. As a rule of thumb, the longitudinal ductility, as determined by the reduction of area, should exceed 80 percent of the planned maximum reduction.

Table 1 lists successful cold forging reductions on a variety of materials from recent barrel evaluations of both rifling and combined rifling and chambering. All of the alloys were fully heat treated. These results indicate that barrels can be cold forged from a great variety of alloys if the machine has sufficient capacity.

Proper material preparation is also a critical requirement for rotary forged barrels because the bore surface requirements are stringent. Preforms are typically gun drilled after heat treatment and turned or ground on centers to 0.005 in. TIR. Good production practices will produce a gun drilled bore of 40 to 60 microinch AA,

Material	Hardness (Rc)	Barrel	Reduction (%)	Remarks	Reference
Cr-Mo-V (barrel steel)	32–33	M21 (7.62 mm)	13–18	Special tooling[(a)]	4
Inco 718	28	M134 (7.62 mm)	25		6
Armco 21-6-9	14.5	M134	25		
U700	42	M134	25	Microtears ~0.001 inch deep at bore	
CG27	36	M134	25		
Inco 718	35–37	M134	10–12	Special tooling[(b)]	7
	44–46	M134	10–12	Special tooling[(b)]	
Vasco M-A	35–38	M134	10–12	Special tooling[(b)]	
H11	36/38	M134	23–28		8
	36/38	M134	23/36	Rifling and chambering	
	36/38	M219 (7.62 mm)	23–27		
U700	40–41	M134	22–30		
	40–41	M134	34	Microtears	
	40–41	M134	23/36	Rifling and chambering	
IN 903	38–40	M134	25–32		
		M134	24/39	Rifling and chambering	

(a) Swage tooling for residual stress control (~0 residual stress).
(b) Small overgrind swage tooling.

Table 1

reduce mandrel life. Reaming or forging on an oversized smooth mandrel in preparation for final forging will improve bore surface finish.

Process parameters are selected to achieve dimensional and strength requirements at an acceptable barrel cost. However, compared with other metalworking processes, there are many parameters involved in rotary forging of rifle barrels and broad generalizations of these parameters may not be adequate in determining system response. To better understand the relationships between the process parameters and the machine and product responses, instrumented swaging trials and quantitative product inspections were performed and the resulting data were related to the process parameters by regression analysis and analysis of variance.(2) These relationships demonstrated that overgrind, reduction, and die angle are of greatest significance to system response.

Other Products for Rotary Forging

Rotary forging equipment manufacturers maintain large displays of prototype parts made during process and machine developments or as part of acceptance trials. A small fraction of these parts are disclosed in promotional brochures. In many cases, technology developed for small parts (less than two inch diameter) is directly applicable to larger parts. Current items in foreign production are drill pipe couplings and a great variety of step shafts, particularly for axles. Relevant potential production items are constant twist rifling configurations of improved designs; rocket nozzles in thin wall structures; OD and ID contoured projectiles or projectile bodies; and torsion tubes and rods. The major impediment to the utilization of the precision, productivity, and material efficiency of rotary forging has been the high cost of the advanced production equipment, which usually requires substatial dedicated production for write off of capital investment.

References

(1) Barth, C. F., and DiBenedetto, J. D., "Improved Materials and Manufacturing Methods for Gun Barrels", Final Report on U. S. Army Contract No. DAAFO3-72-C-0170 (June 1975).

(2) Hoffmanner, A. L., and Iyer, K. R., "Rotary Swaging of Precision Barrels", Final Report No. R-TR-74-050 on U. S. Army Contract No. DAAFO3-73-0005 (September 1974).

(3) Drennen, D. C., Jackson, C. M., Miclot, R. B., and Iyer, K. R., "Rotary Swaged Rapid-Fire Gun Barrels" Final Report on U. S. Army Contract No. DAAFO3-70-C-0005 (August 1972).

(4) Hoffmanner, A. L., DiBenedetto, J. D., and Iyer, K. R., "Improved Materials and Manufacturing Methods for Gun Barrels (Part II)", Final Report on U. S. Army Contract N. DAAFO1-71-C-0410 (September 1972).

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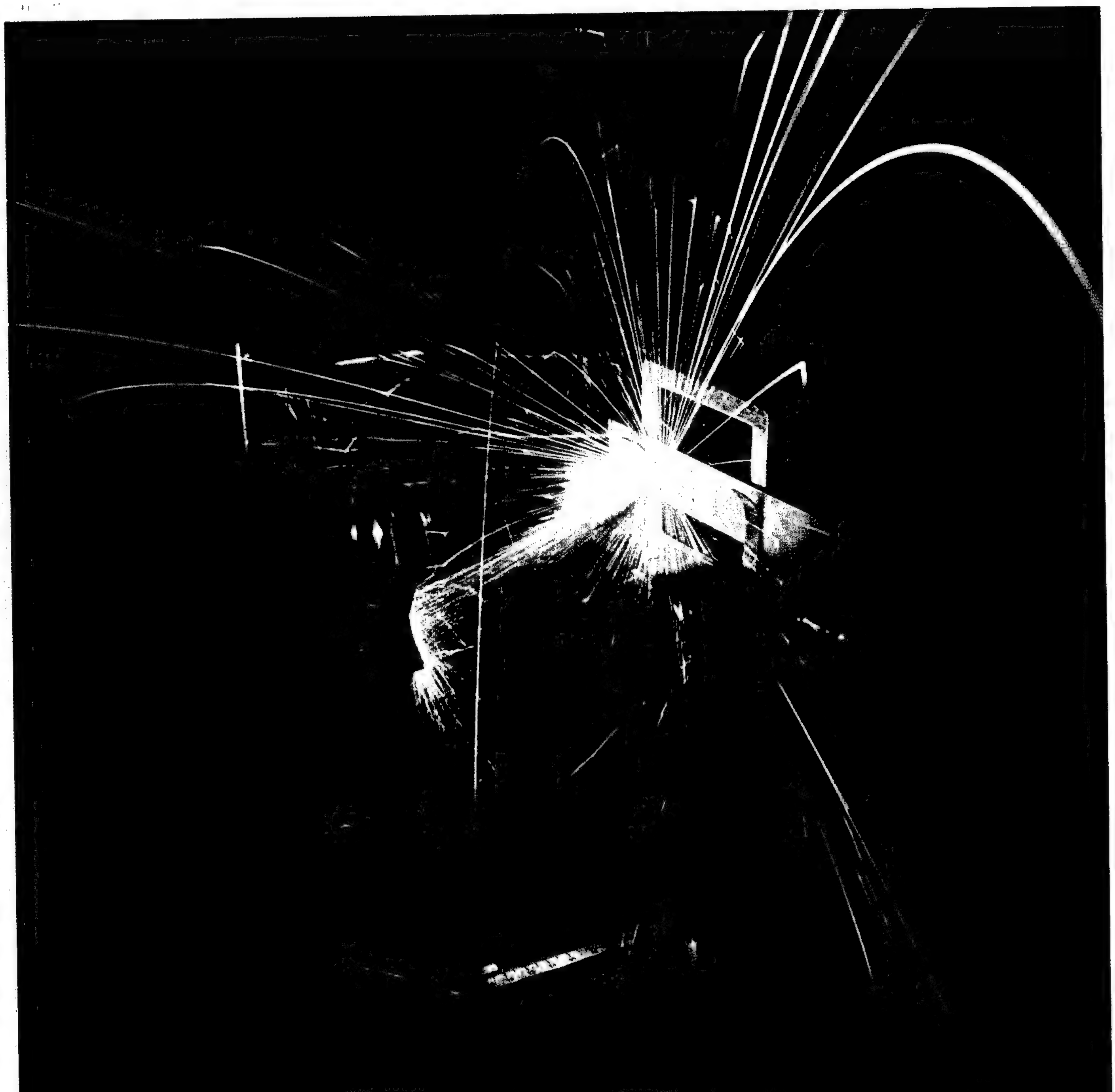

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ABOUT THE COVER:

Laser drilling of holes in titanium plate is seen in this fiery photo taken in the General Electric Aircraft Engine Group laboratories in Cincinnati. The Air Force sponsored MT project has reduced turbine blade costs by utilizing lasers to drill blade cooling holes of 0.008 to 0.050 inch diameter up to depths of 0.750 inch. These cooling holes are difficult to produce in conventional materials, but even more so from high hardness materials. Laser drills now are being used in routine production, reducing drilling costs from 20-90 percent depending on blade design; one contractor estimates his savings at $1.5 million/year. The maturation of the process is expected to permit new design concepts for turbine blades to evolve.

Comments by the Editor

RAYMOND L. FARROW

This issue of the U.S. Army ManTech Journal marks the first of several changes to be brought about in the publication to provide better, more easily used information about the Army's new manufacturing technology developments. These changes will be reinforcement of our primary overall purpose—acceleration of the exchange of information about these new manufacturing technologies through reports on manufacturing and management techniques newly implemented by the Army. As presented in our formal statement of purpose on the back cover of each issue, communication will be enhanced within the Army technical community, with our sister services, with other Government R&D agencies, and with industry—especially all those who are deeply involved with modernizing our manufacturing base in the United States. Army manufacturing development activities will become more widely known, promoting more cost effective overall production, both in the military and in industry.

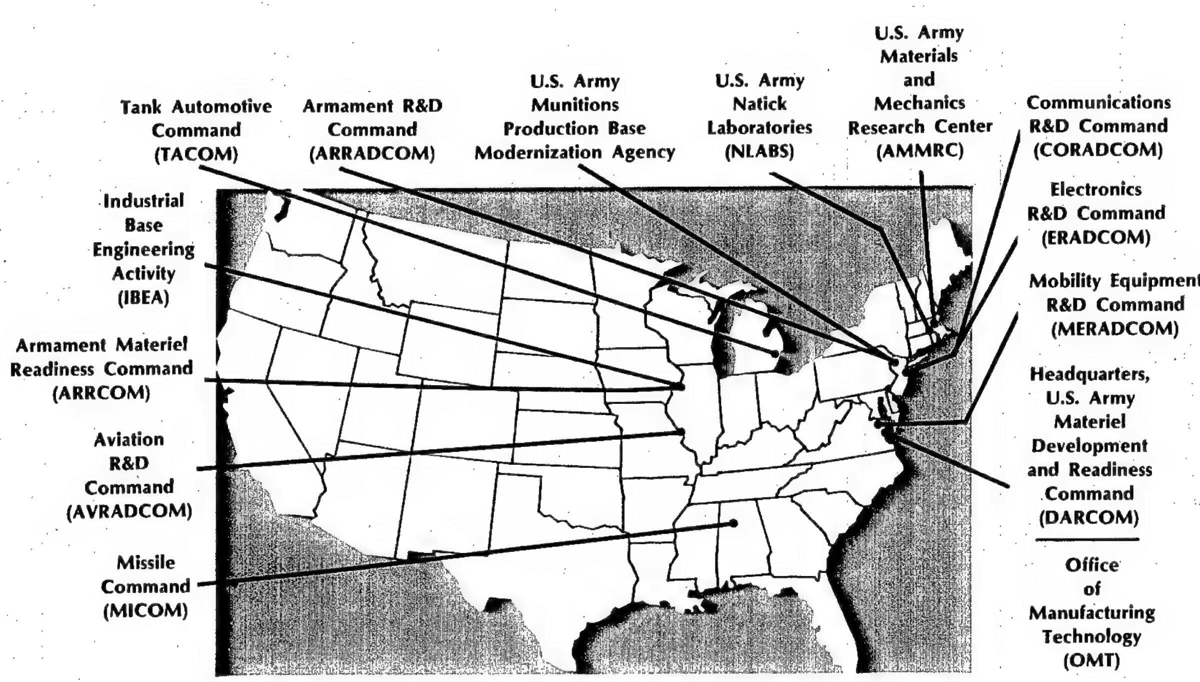
The additions to this issue include the name and telephone number of the appropriate Army engineering representative who directly monitored the specific project discussed in each article in this issue. These notes will be found in small boldfaced, boxed in statements on the first page of each article. In some cases the name is the same as that of the author, and in some cases—particularly when the author is an engineer with an industrial firm, the name is that of the engineer who still is monitoring implementation of the work that was funded by his particular agency or command. The editorial staff feels this to be a prime piece of information for those who are most interested in following further developments in this particular area—a piece of information that will save valuable time for the inquirer.

The manufacturing technology projects on which the articles in the Army ManTech Journal are based are conducted by the various major subordinate commands of the U.S. Army Materiel Development and Readiness Command (DARCOM) under the overall direction of the DARCOM Office of Manufacturing Technology (OMT). The six subcommittees of the DoD Manufacturing Technology Advisory Group (MTAG)—with representatives from all three military services and civilian industrial organizations—also are active in the overall monitoring of manufacturing technology projects conducted by the three services. For example, the DARCOM Office of Manufacturing Technology assigns engineering personnel to monitor these projects. These OMT monitors serve on various MTAG subcommittees and report on the projects to their subcommittees, thereby directly placing the MTAG subcommittees into the monitoring loop.

The articles carried in the Army ManTech Journal represent the prime comprehensive condensation/review of these projects that is presently available to the general public and manufacturing circles outside the MTAG structure. Each article generally is based on the final report of that particular project and reflects anywhere from two to five man-days of highlighting review by technical writers. A report of over 150 page length will be briefed to perhaps four to ten pages for efficient, quick review by busy engineering executives. The investment in time to perform this task is considerable, but forms the basis for the stated purpose of this Journal. The editorial staff strongly believes this to be a significant time-saver.

Another new major change of policy the editorial staff plans is to invite outstanding experts in various fields of manufacturing to submit guest editorials to the magazine. There are many experts representing thousands of years of experience in manufacturing who have important information for those of us involved in this national self-improvement effort. It is fitting that this information also be included for our general readership. Individuals interested in providing all of us an insight into their respective expertise should submit their thoughts to the Editor for inclusion in future issues.

DARCOM Manufacturing Methods and Technology Community



Less Machining, Material Required

Hot Dies for Titanium Forgings

With recent developments and advances, hot die forging of titanium alloys has become an acceptable manufacturing process for aircraft structural and engine components. Using the process, a fabricator can forge more refined shapes, better utilize costly titanium alloys, cut machining costs, and use fewer forging operations. These improvements are possible because the hot die reduces or eliminates die chilling of the material and strain hardening.

Tooling systems, lubricants, die materials, and forging process variables for manufacturing near net shape parts in sizes up to a 600 square inch plan area are now available. Much of the development work has been done under Air Force contract at Wyman-Gordon Company and other forging companies.

Cost effectiveness of the process has not yet been demonstrated over a wide range of structural components, but with its other advantages, hot die forging is being used increasingly to manufacture titanium airframe and engine parts. As titanium cost and availability problems increase, the importance of this technology continues to grow.

Substantial Savings Possible

With alpha-beta titanium alloys such as Ti-6Al-4V, cost effectiveness depends on the part quantity, size, and shape. Precise cost comparisons to conventional forging are difficult because of the variations of these parameters with the part selected, but Figure 1 shows relative estimated costs per unit as a function of the number of units for an F-15 bearing support (600 square inch plan area) and connecting link (140 square inch plan area); both parts are made from Ti-6-4. It is obvious that when sufficient parts are run, hot die forging becomes very attractive from a cost standpoint.

Allows Near Net Shapes

In hot die forging, die temperature is the same as, or slightly below, the forging temperature of the alloy; i.e., the process includes both isothermal and near isothermal forging. For Ti-6Al-4V, the forging temperature is about 1750 F. As the die temperature approaches that level, metal flow can be closely controlled by the processing variables—forge temperature, ram rate, preform microstructure, strain, strain rate, forge pressure, and dwell time.

Conventional forging, on the other hand, uses die temperatures below 800 F and ram rates above 10 in./min. At these conditions, die chilling (especially for thin section forgings) and strain hardening play significant roles, and forgeability at a given forge temperature is appreciably reduced. The use of hot dies and relatively low ram rates with close control of flow appears to improve this situation. As a consequence, near net shape forgings become possible. The traditional material allowance between the as forged shape and the finish machined

CHARLIE C. CHEN currently is President of Chen-Tech Industries, Inc., a high technology company dedicated to the development and manufacture of high technology forging products and to the implementation of cost effective and productive manufacturing technology. He received his M.S. and Ph.D. degrees in Metallurgical Engineering from the Michigan Technological University. He has been the Group Leader in the Research and Development Department of Wyman-Gordon Company responsible for hot die forging, titanium alloy studies, and other metallurgically related problems. His work at Wyman-Gordon during 1974-1980 was concerned with various aspects of forging technology ranging from processing to structure and properties of various alloys, particularly in Ti base and Ni base alloy forgings. He has served as program manager and/or project engineer for several government and industrial R&D contracts in the areas of Ti alloy technology. He is author and coauthor of more than 50 technical papers and reports in the areas of physical metallurgy and metallurgical engineering and has presented more than 50 technical presentations in the past 4 years. He has served as committee member for several professional societies and is currently an active member of the Titanium Committee of AIME, and the Process Modeling Activity Committee of ASM.

NOTE: This manufacturing technology project that was conducted by Wyman-Gordon Co. was funded by the U.S. Air Force Materials Laboratory. The AFML Project Engineer is Norman E. Klarquist (513) 255-2413. W. H. Couts, Jr., and C. P. Gure are Wyman-Gordon associates on the project.

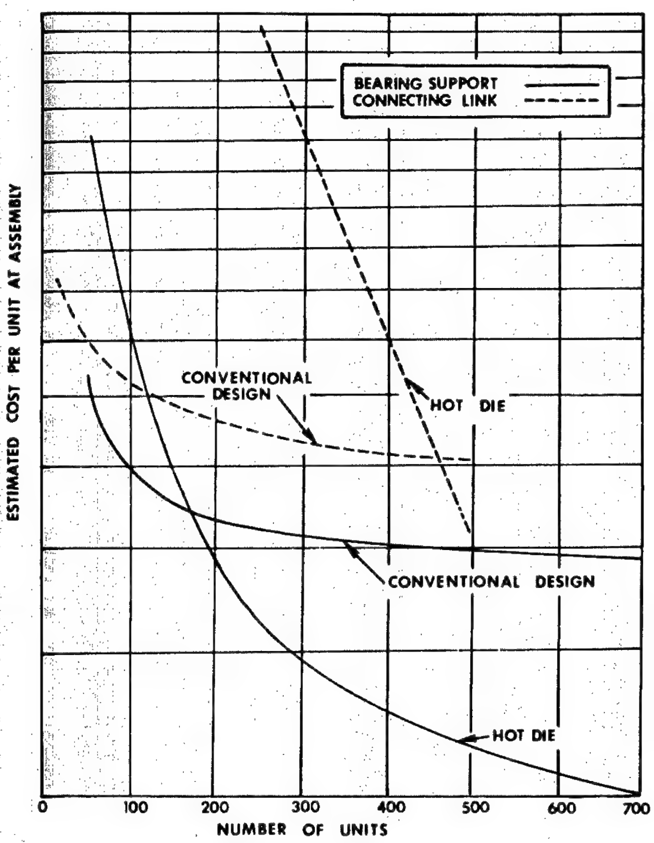


Figure 1

shape is significantly decreased, and excess material can be removed easily by chemical milling or very limited machining.

Die Material Important

Earlier development of titanium hot die forging concentrated on isothermal forging. For alpha-beta alloys with forge temperatures in the 1700-1800 F range, IN-100 cast dies and induction heating tooling were required. However, both structural and property stabilities of IN-100 are a serious problem at these operating temperatures, and the cost effectiveness of the process in manufacturing applications becomes questionable.

Wyman-Gordon has sought to improve both the efficiency and cost effectiveness of hot die forging during their Air Force studies. Results of experiments on forge temperature, die temperature, and strain rate interactions indicate that reducing the die temperature to 1600-1650 F and increasing the ram rate to 3-5 in./min increases die stability and strength. This allows a more dilute, less expensive nickel base alloy to be used as a die material. As a result, a tooling system using Astroloy die inserts and modular design concepts to accommodate a range of part sizes was developed. The potential cost effectiveness of this hot die system was demonstrated in a relatively large procurement of the F-15 bearing support and connecting link. The application of hot die technology has been further substantiated during extensive efforts to determine the forgeability, structure, and properties of various titanium alloys. In these programs, particular emphasis was placed on the commercial alloy systems such as Ti-6Al-4V, Ti-6Al-2Sn-4Zr-2Mo-o.1Si (Ti-6242Si), Ti-6Al-6V-2Sn, Ti-17, and Ti-10V-2Fe-3Al (Ti-10-2-3).

Metallurgical Factors Studied

These studies concentrated on a better understanding of the nature of metallurgical properties. The major metallurgical factors considered were deformation processes, structural characteristics, and mechanical properties. Several conclusions were drawn from these studies. Obtaining satisfactory near net shape forgings requires the proper forge temperature, die temperature, strain rate, and preform microstructure. Adequate control of these variables can maximize the forgeability of the alloy and optimize the resultant microstructure and properties of the forgings.

It was found that the deformation characteristics during forging are qualitatively related to the hot deformation properties of the alloy. On the basis of experimental findings and activation analysis, the rate controlling deformation process in alpha-beta forgings is attributed more to their dynamic softening than to more conventional rate controlling mechanisms.

Structural characteristics of forgings vary significantly with die temperature, strain rate, stock temperature, strain, and preform microstructure. These parameters must be closely controlled to obtain desirable microstructures.

Mechanical Properties Improved

In addition to deformation and structural characteristics, the mechanical properties of the forgings are significantly affected by hot die forging. Results indicate that, when compared with conventional forgings, hot die forgings made under proper conditions generally have superior, more uniform fracture toughness, tensile ductility, and creep properties. These properties, however, depend critically on forge temperature, die temperature, and preform microstructure.

Fracture toughness of the forgings generally increases as the die temperature increases. By controlling the die temperatures slightly below the beta-transus temperature, the relatively low ductility of the beta forgings can be significantly improved in hot die forgings. The creep resistance of Ti-6242Si increases significantly in isothermal forgings. There is a slight increase in yield strength and ultimate tensile strength with decreasing die temperatures and with increasing strain rate for both alpha-beta and beta forgings.

Problems Remain

As noted, dies with Astroloy inserts have proven more cost effective than the previous IN-100 dies. However, there are still problems. Both dies permit satisfactory properties for alpha-beta forgings at die temperatures at or below 1650 F, but both structural and property stability of these alloys become serious problems at higher operating temperatures. Thus, the strength capability and high temperature stability of die alloys need to be upgraded.

From the standpoint of strength and stability, TZM is a very satisfactory die material at service temperatures up to 2200 F and is being used for some hot die forging. However, to prevent oxidation, TZM dies must be used in a protective or vacuum atmosphere. Furthermore, costs for the basic material, die production, and the required oxidation protection are very high and the need for a controlled atmosphere limits press capacity. A more practical and economical approach is to develop a nickel base superalloy or other high oxidation resistance alloy that satisfies technical requirements for hot dies in air.

An alternative approach to reducing die costs for titanium alloys is to use a lower die operating temperature. A die temperature of 1200-1400 F would reduce the cost of die alloys. A survey of possible candidate die alloys suggests that less expensive and non-cobalt containing nickel base alloys, such as Inco-901, might meet requirements. Inco-901 costs about one third as much as cast IN-100. The drawback to this approach is that, at lower die temperatures, alpha-beta alloys cannot be forged as near to net shape as at the higher temperatures, so the purpose of hot die forging is partially defeated.

Lubricant Considerations

Another problem involves process lubricants. There are several lubricants already developed for hot die forging of alpha-beta titanium alloys. All of these have excellent adhesion properties, long term thermal stability, good chemical compatibility with die materials, and other basic lubrication features. And, unlike the dual lubricants (forging and die lubes) used in conventional forging, current hot die forging uses a single lubricant—generally, a glass type coating on the workpiece.

However, none of the available lubricants for hot die forging of alpha-beta alloys provides a satisfactory balance of the lubricity and adhesion properties for manufacturing applications. Thus, there is a need for new lubricant formulations with improved lubrication effectiveness.

Water Base Lubricants Studied

There are two recommended approaches to improved hot die forging lubrication for alpha-beta alloys. First, investigations of water based boundary lubricants that contain dispersed solid film powders as an interface separation agent and inorganic binder as a wetting agent for the workpiece should continue. The wetting component may be either a ceramic compound or an improved glass type composition. The new lubricant formulations should be able to provide the combined advantages of improved stability in gas fired environments, excellent antifriction characteristics, low die to workpiece adhesion, low accumulation rate, and less corrosive action.

Parting by Lubricant

The second approach is to apply the die lubricant as an efficient parting compound between dies and workpiece. The die lubricants must adhere effectively, allow repeated application to the dies at high temperatures, and must not react with the workpiece coating.

A final major obstacle to the current hot die technology for alpha-beta alloys is the high energy consumption necessary to heat dies and maintain them at high temperatures. Since poor thermal conductivity of nickel base alloys may impose difficulties in achieving faster heatup of tools, the use of higher conductivity die alloys may be helpful in reducing energy consumption. This can be achieved more easily with beta titanium alloys because of their greater availability for use at lower die temperatures.

Despite the problems that still exist, the use of hot die forging with titanium alloys continues to grow. Examples of current applications to near net shapes are the F-15 bulkhead center body (Ti-6-4), CFM-56 engine fan disks (Ti-17), JT-8D first and second stage compressors (Ti-6.4), and the F-100 first stage compressor (Ti-6Al-2Sn-4Zr-6Mo). The F-15 center body is shown in Figure 3. Hot die forging of Ti-6242Si disks for JT-9D compressors is another potential application.

Beta Alloys More Attractive

Figure 2 compares estimated costs per unit for the isothermally forged F-15 bulkhead center body for Ti-6-4 and Ti-10-2-3 alloys. The cost effectiveness of hot die forging is seen to improve significantly with the beta alloy (Figure 3). Thus, the use of beta alloys could be a key to further improvements of both cost effectiveness and structural efficiency for hot die forging to titanium near net shape structural components.

The technology should have excellent potential in the manufacture of dual property titanium disks and structures for improved efficiency and cost. Dual microstructure pancakes have been isothermally forged from a Ti-6242Si composite preform. The pancake has a pseudo-beta microstructure in the rim area which should provide excellent creep, fracture toughness, and stress rupture properties.

Compressor Fabrication Likely

The globular alpha structure at the bore region should improve LDF, ductility, and strength. If such a dual microstructure forging can be obtained by hot die forging through precise control of processing variables and preform shape, the technology should apply to manufacture of compressors, which are creep critical at the rim area and fatigue critical at the bore region.

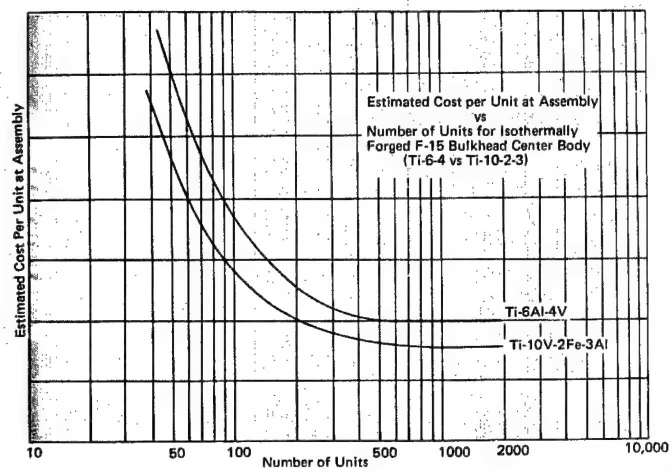


Figure 2

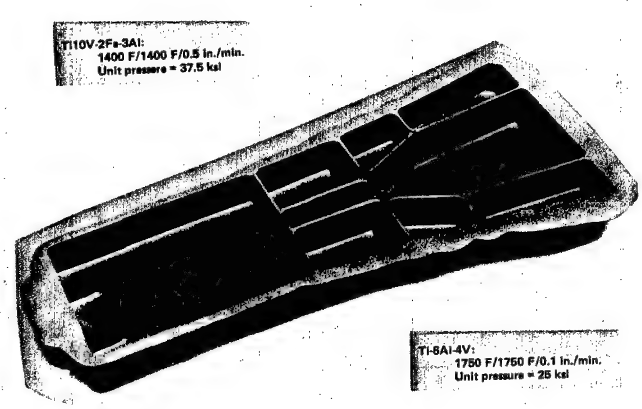


Figure 3

Use of this sophisticated forging process—offering excellent combinations of strength, toughness, and other properties for structural applications—should continue to grow for both alpha-beta titanium structural forgings.

No Photo Available

STEPHEN KRUPSKI has been a Metrology Engineer in the Inspection Engineering Division, Product Assurance Directorate, at Watervliet Arsenal since 1975. He recently has been involved as a Project Engineer on several MM&T funded projects. He holds a Bachelor of Mechanical Engineering degree from Rensselaer Polytechnic Institute.

Ultrasonic Inspection of Hot Cannon Tubes

Broader Applications Foreseen

Work at Watervliet Arsenal on rotary forged cannon tubes has extended the capabilities of ultrasonic thickness measurements to use with materials at elevated temperatures. Standard transducers and oil coupling cannot be used to check wall thickness variations on hot tubes. Because early detection of such variations is critical, Watervliet has developed the new system using pressure coupling to permit elevated temperature monitoring. A traveling carriage is holding four transducers that make comparative measurements through the cross section at different points on the tube. The maximum variation in these measurements is computed and displayed, quickly revealing any nonuniformities.

The system has many other potential industrial applications—inspection of steel piping and steel plate that require thickness checks at high temperature, for example. The major advantage of a high temperature capability is the prevention of out of control production that can occur if parts have to cool before monitoring. Many defective parts can be fabricated while inspection waits out an extended cooling period. Early detection will allow early correction of any fault.

Vital For Rotary Forgings

The need for ultrasonic thickness monitoring at high temperature arose when a rotary forging machine was installed at Watervliet in 1975 for cannon tube production. Using this machine, cannon tubes with 2.5 to 8 inch diameter bores are forged from hollow preforms. The amount of waste material in the forgings is sharply reduced, resulting in sizeable cost savings in tube fabrication. A conventional 105 mm M68 forging requires 8400 pounds of starting material compared to just 3000 pounds for a rotary forging. The finished M68 tube weighs 1660 pounds.

NOTE: This manufacturing technology project that was conducted by the Product Assurance Directorate at Watervliet Arsenal was funded by the U.S. Army Armament Materiel Readiness Command under the overall direction of the U.S. Army Office of Manufacturing Technology, DARCOM. The ARRCOM Project Engineer is Mr. Stephen J. Krupski (518) 266-5523.

The computer controlled rotary forge produces an M68 gun tube preheated to 1800 F in approximately 11 minutes, or 40 tubes in an 8 hour shift. Close monitoring of wall thickness in these rotary forged tubes is critical because of the small amount of excess material. Without uniform wall thickness to insure even material distribution, there would not be sufficient stock for final machining operations.

Early Inspection Vital

Furthermore, to prevent production losses, nonuniformities must be detected as soon after forging as possible. Using conventional inspection techniques, any malfunction in the forging process that leads to nonuniform wall thickness is not detected until the forging has cooled. While a cannon tube forging cools to approximately 100 F, 40 more tubes can be forged. All of these could have the same unacceptable wall thickness characteristics. Thus, early inspection is vital.

What are some very practical reasons that conventional inspection processes cannot be applied to hot tubes? Wall thickness of cannon forgings is normally monitored ultrasonically with transducers applied to the tube surface by hand. Ultrasonic coupling is established between the transducer and the tube by placing a small puddle of oil at each measurement point. This is not possible with rotary forgings that are still hot. First, the transducers won't withstand contact with the hot material. Second, application of the transducer by hand would be dangerous. Finally, the oil used to establish coupling would burn or evaporate instantly. The need for a new technique was obvious.

Initial Development

To meet this need, Watervliet first prepared a specification defining the requirements of a system to measure wall thickness variation of cannon tubes immediately off the forge machine. Based on this effort, work was begun with Sonic Instruments of Trenton, N.J., to design such a system. Initially, tests were undertaken to determine if Sonic's approach to the problem would be successful.

These tests were run at Watervliet using a standard ultrasonic transducer, a watercooled aluminum delay line, and a hand operated arbor press. Sections of actual forgings were heated in a small furnace to approximately 1700 F—the temperature of rotary tubes immediately off the forge machine. Transducers were applied to the test samples under a 2000 pound force to attempt to establish ultrasonic coupling. The theory was that deformation of the cannon tube surface at this temperature would be sufficient to establish coupling. Readings were obtained on a standard readout system with varying degrees of accuracy and repeatibility. Alignment of the delay line with the sample centerline, as well as configuration of the delay line, proved critical. Three delay line configurations were tested to determine which gave the strongest signal and the signal that stood clearly above background reflections.

Alignment Essential

Aluminum and copper sheets tested as couplants between the delay line and sample slightly reduced the required pressure. Lead sheets were also tested which reduced required pressure to a very low level. However, the lead melted away too quickly at test temperatures and would be useful only if measurements were to be taken at a medium temperature.

Tests showed that pressure coupling was feasible down to approximately 900 F as long as the delay line was aligned on the forging centerline. The delay line configuration was finalized with the use of a 4 inch spherical radius on the tip. Any reflections from the tip of the delay line should bounce back to the same point, thus giving a signal on the CRT screen. Making this signal occur at 4 inches put it just beyond the maximum thickness to be measured. The delay configuration is illustrated in Figure 1.

System Operation

Based on this testing, a wall thickness variation measurement system was designed and constructed. This system is built on a traveling carriage that rides on two tracks and supports the transducers. The motorized carriage can be stopped at each measurement interval

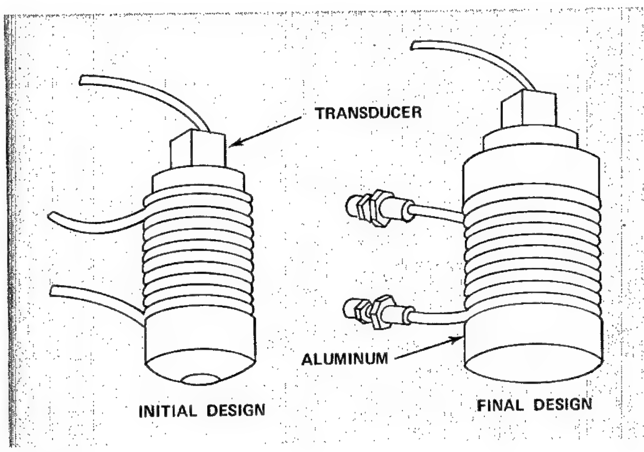


Figure 1

required as it moves along the cannon tube, which is supported on three V-block stands as shown in Figure 2. These stands are carefully positioned for each different tube to minimize bending of the tube. Support positions are critical because the yield strength of these forgings is substantially reduced at high temperatures.

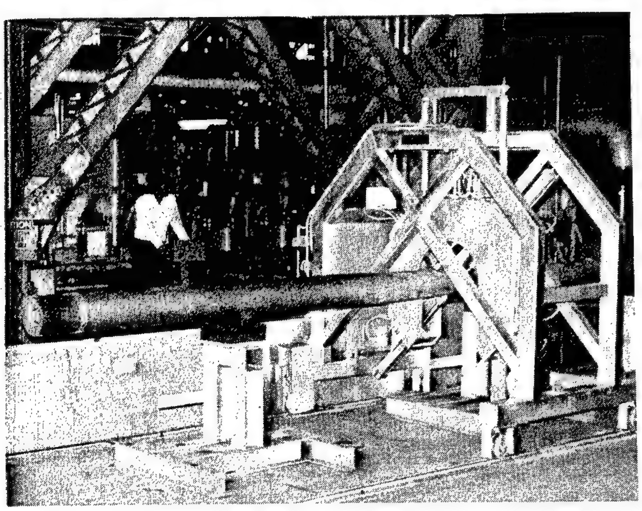


Figure 2

Four ultrasonic transducers with watercooled delay lines are mounted 90 degrees apart on the carriage. Each is controlled by a long stroke hydraulic cylinder that holds the transducer against the forging with a force of about 2000 pounds. Transducers contact the forging surface at four equally spaced points to measure wall thickness variations at a particular cross section (See Figure 3).

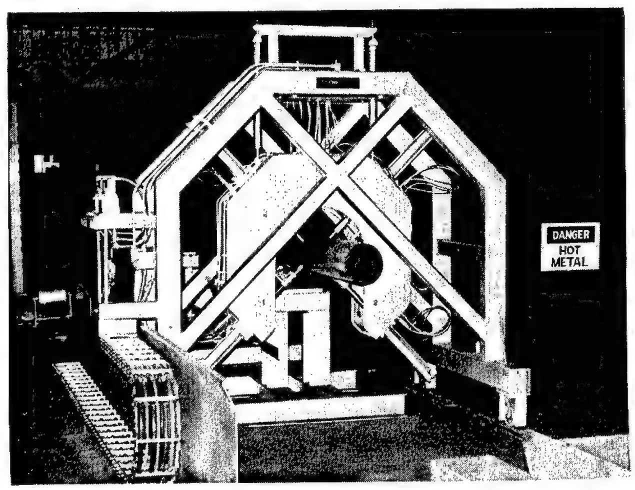


Figure 3

Recalibration Not Required

The transducers are connected to readout devices in a heat insulated cabinet. At each monitoring point, the four wall thickness readings are displayed and printed along with their measuring positions. A microprocessor computes the variation between minimum and maximum readings and prints the wall thickness variation. Hydraulic motors then move the yoke to the next selected cross section and the process is repeated.

Although the system does not yield accurate thickness measurements because of the high temperature and corresponding decreased sound velocity, it does measure thickness variations accurately since temperature is constant around the forging at each cross section. Thus, nonuniformities are clearly identified. The temperature gradient from one end of the tube to the other also makes it difficult to get accurate wall thickness readings. But

since the main concern is the uniformity of wall thickness, there is no need to recalibrate the readout at each temperature.

The entire wall thickness variation measurement system is controlled by the operator from a small console (shown in Figure 4). Controls include start-stop switches for

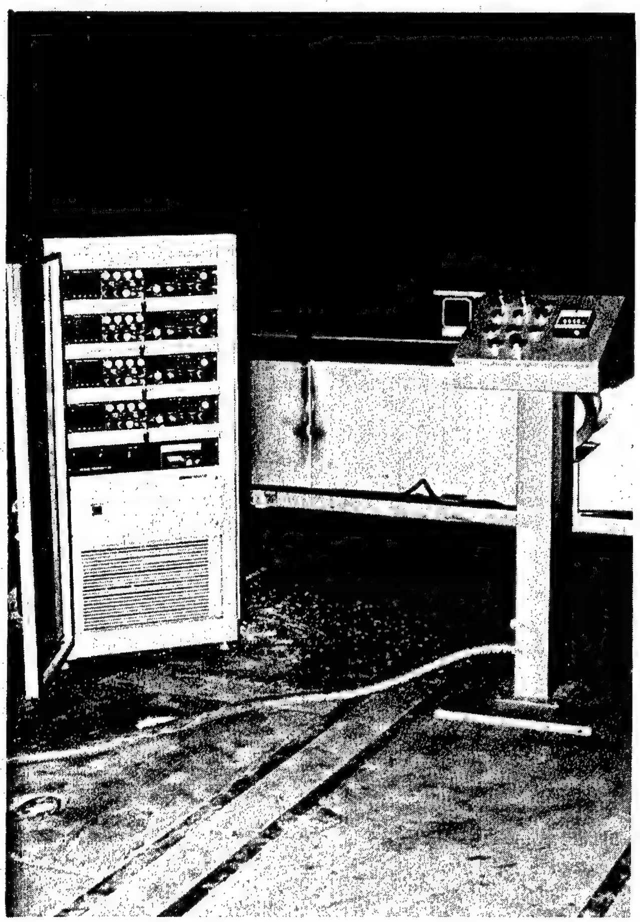


Figure 4

hydraulics and water, grip and release buttons, carriage forward, reverse, and stop buttons, and a switch for the warning horn for cooling water loss.

All Four Measurements Mandatory

To initiate measurement, the operator pushed a button to move and position the carriage to the first test point on the tube and then pushes the grip button to bring the four transducers in contact with the forging under pressure. The system automatically scans the four transducers for signals. If all four signals exist, the four readings are printed, together with the maximum variation. If one or more signals are not detected, the transducers are released and retracted from the forging. The operator then presses the grip button again and the process is repeated.

Once a reading is recorded, the operator moves the carriage to the next test position and presses the grip button again. The process is repeated until all required test sections are measured. The result is a record of wall thickness variation of the forging (Figure 5) that is

	4--	02.05		4--	03.40
	3	02.07		3	03.44
POSN 2	2--	02.06	POSN 4	2	03.47
	1+	02.08		1+	03.47
	0	00.03		0	00.07
	4	01.87		4--	03.42
	3--	01.85		3	03.45
POSN 1	2	01.87	POSN 3	2+	03.48
	1+	01.91		1	03.45
	0	00.06		0	00.05

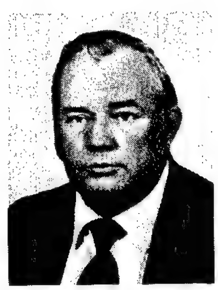
105 mm, M68 – Max Allowable Variation 0.150

Figure 5

available approximately 15 minutes after the tube is forged. Evaluation of the data will indicate any tendency that might lead to production of unacceptable tubes. Based on this data, decisions can be made to either adjust or stop the forging process before a large number of unacceptable tubes are produced. Clearly advancing the capabilities of ultrasonic inspection, the system should become an important inspection tool in the forging industry.

Required by Increased Density

Heat Pipes Cool Circuits



LOYD WOODHAM is Project Manager in Computer Aided Design and Computer Aided Manufacturing, System Engineering Directorate of the Army Missle Laboratory, U.S. Army Missile Command. He came to Redstone Arsenal in 1958, starting in the U.S. Army Missile Electronics Laboratory after graduating from Smith—Hughes, Atlanta, Georgia, in Electronics Technology. Among his first assignments was technical support in the assembly of the Army's Redstone tracking station, which was used to determine Sputnik's orbit and to track a number of later Satellites. He later transferred to the Advanced Sensors Directorate and became a Group Leader. He established and managed the first printed wiring board manufacturing facility at Redstone, which grew into the System Engineering Directorate's existing facility. He started work in the Manufacturing Technology Division in 1977.

Development of cost effective manufacturing techniques for heat pipes used to cool electric system circuit cards at Hughes Aircraft should allow significant improvements in electronic systems. Reliability of the production line techniques, which resulted from work conducted for the U. S. Army Missile Research and Development Command, has been thoroughly demonstrated. Although these techniques were developed for a particular circuit card configuration, they have much broader application. Significant results in the area of heat pipe design were also obtained, with integrated pipes proving most effective.

Increasingly sophisticated electrical systems with more densely packaged components require circuit cards with greater power and density. This in turn creates greater demands for removal of heat from the cards. Conventional cooling techniques have not kept pace with these demands, preventing further growth in system capacities. Although the use of heat pipes to solve this problem had been demonstrated, such efforts had not gone beyond custom made pipes. For the widespread use needed for such systems, new production techniques that reduce costs and ensure reliability are required. To meet this need, Hughes undertook a project in which they analyzed cooling pipe design, manufacturing methods, and production systems, seeking to optimize developments in each of these vital areas.

Because most electronic equipment systems assemble components in the form of a circuit card, the configuration used was that of a card thermal mounting plate, as shown in Figure 1. High power systems use thermal mounting plates to conduct the heat energy dissipated by the component to a heat sink in the manner shown here for a heat pipe.

For this developmental effort, Hughes used the heat pipe card shown in Figure 2. This is a representative configuration of a 5x6, 50 watt, dual in-line package. While the technology developed was directed to this design, it is applicable to fabricating practically an unlimited number of other configurations that would benefit from heat pipe cooling.

Hughes' manufacturing methods are based on mass production techniques using a stand alone manufacturing line with conventional manual and semiautomatic equipment capable of filling and sealing fifty heat pipes per hour. The system is designed for a multiple station operation, with additional stations easily added if needed to increase output.

In developing the circuit card design and the manufacturing process, Hughes conducted an extensive analysis to determine the optimum materials and processes to be used. After selections were made, a testing and

NOTE: This manufacturing technology project that was conducted by Hughes Aircraft was funded by the U.S. Army Missile Command under the overall direction of the U.S. Army Office of Manufacturing Technology, DARCOM. The MICOM Project Engineer is Mr. Lloyd Woodham (205) 876-5742.

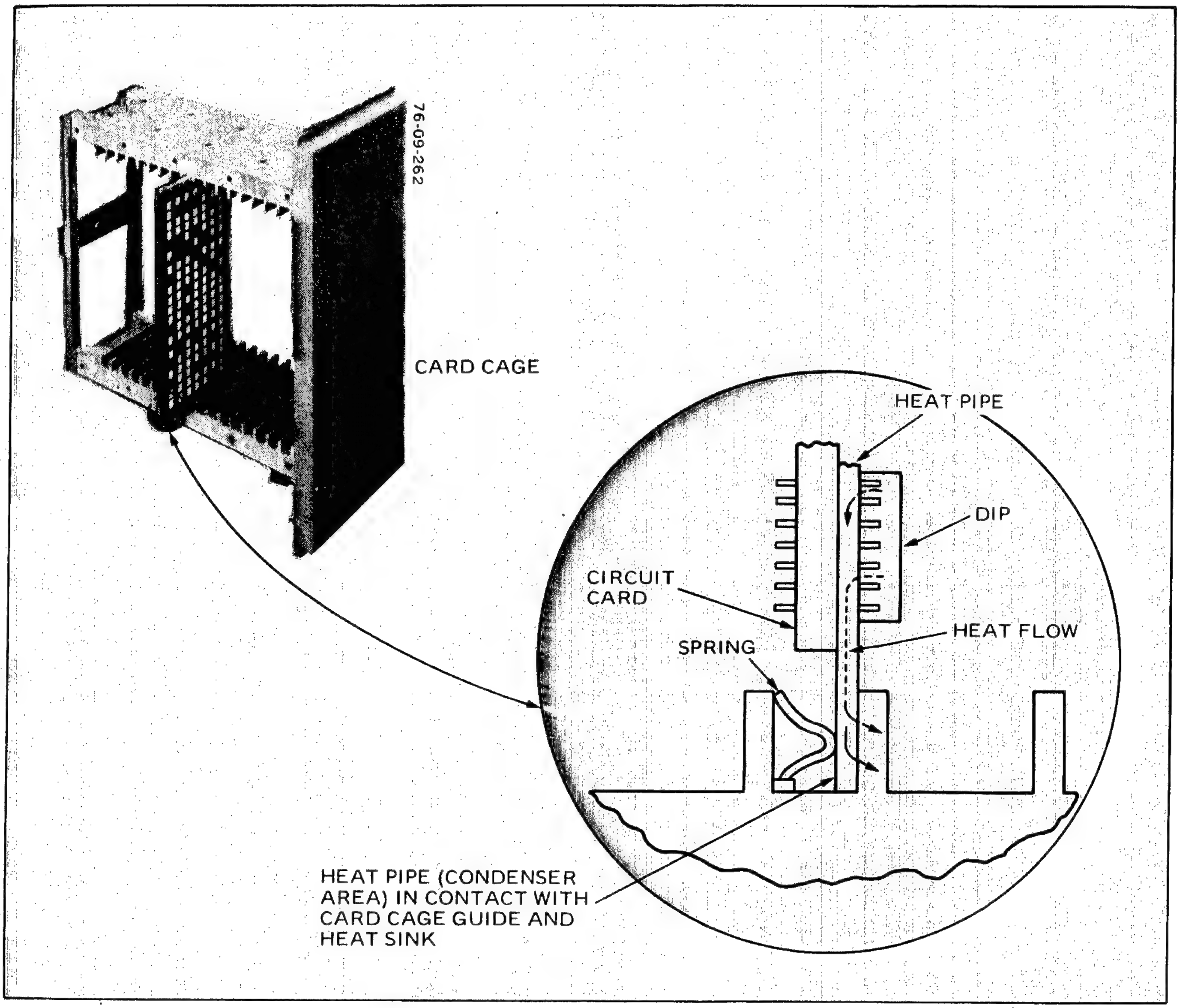

76-09-262
CARD CAGE
HEAT PIPE
DIP
CIRCUIT CARD
HEAT FLOW
SPRING
HEAT PIPE (CONDENSER AREA) IN CONTACT WITH CARD CAGE GUIDE AND HEAT SINK

Figure 1

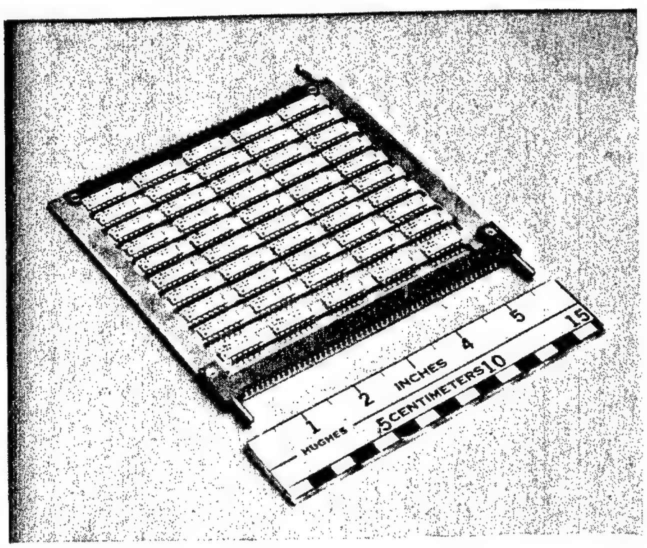


Figure 2

development program was conducted to determine the best production materials and methods to use in manufacture.

Integrated Design Selected

Two heat pipe designs were considered—one in which the heat pipe is an integral part of the card and one using a number of individual heat pipes attached to a metallic header that interfaces with the heat sink. Based on thermal performance, size, weight, and adaptability to heat sink cards, the integrated design was selected. Individual heat pipes require additional thermal interface. The high power density at these interfaces results in higher temperature gradients in the individual heat pipe modules. Although this could be overcome by increasing the interface area, that would require unacceptably large modules.

The integrated design is compatible with existing electronic equipment. Its major shortcomings are the need for more expensive tooling and problems in obtaining a good hermetic seal over the long seal length. These were not considered as serious as the drawbacks of the other design.

The integrated heat pipe module configuration shown in Figure 3 uses flat pipe. The parallel heat pipe conduction bars are manifolded together at each end. Electronic packages are bonded directly to the top face of the bars and the underside of the heat pipe array is bonded to the top surface of the multilayer printed circuit card. The heat pipe manifolds project beyond the circuit card at each end to provide a large thermal interface area to transfer heat effectively to the heat sink. Because the flat heat pipes provide more surface area for conduction cooling than do other configurations, the thermal resistance between the components and heat pipe interface is minimized.

Efficient Cooling System

Cooling in this system results from a combination of heat transfer and fluid flow techniques. The heat flow path in the heat pipe (Figure 4) starts at the interface where the heat dissipating component is bonded to the heat pipe. Heat flows through the heat pipe shell and then through the evaporator wick liquid matrix to the liquid/vapor interface. After heat energy is absorbed in evaporation of the liquid, the vapor moves to the condenser where the heat energy is released by the condensing vapor. From there, the heat flows through the condenser wick liquid matrix and then through the heat pipe shell to the heat sink. Flow of the condensed vapor through the wicks to the evaporator completes the cycle.

The heat pipe bars to which the electronic components are mounted can be as small as 0.2 inch wide by 0.080 inch thick. Other sizes may be required to achieve effective overall thermal design by matching the heat transfer surface areas of the components. This design is extremely flexible and can be configured with bars of different widths in the same assembly. In addition, nonconstant width bars can also be utilized.

The heat pipe condenser manifolds ensure uniform cooling of all components because heat transfer, regardless of component location, is to the vapor space of the heat pipe. The vapor space is used to transport the heat absorbed in vaporizing the fluid to the condenser manifold where it is released. Thus, all the components are equally coupled to the condensers.

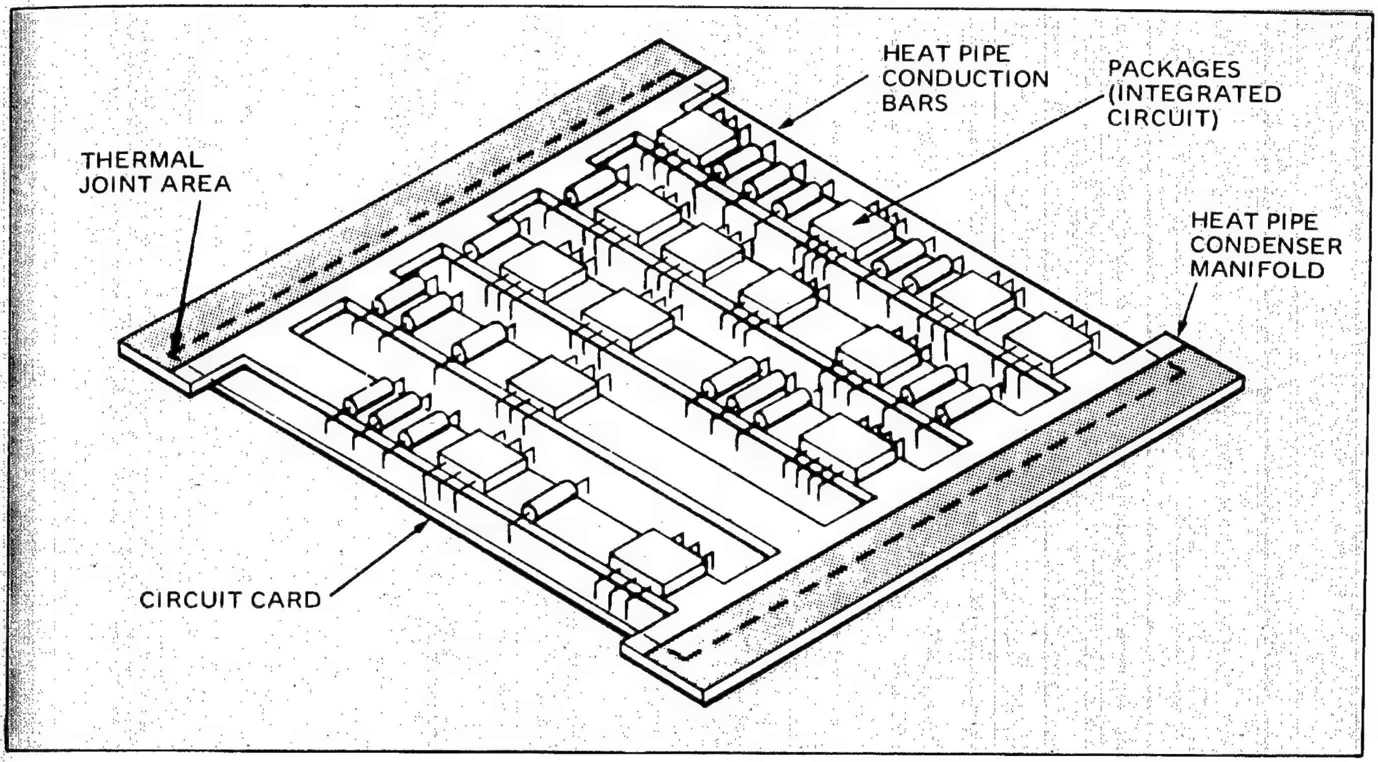


Figure 3

The condenser manifolds are shaped to fit into the card slots which constitute the heat sink for the heat pipe as well as provide structural support for the circuit card. Manifold size and shape can be varied to meet heat transfer requirements and electronic system structural requirements. The entire area of the card slot can be used for direct heat transfer from the heat pipe condenser to the heat sink, minimizing the temperature differentials in the heat pipe and between the heat pipe and the heat sink.

Typical rated power for the circuit card heat pipes is 100 watts for a 12x12 inch card, 50 watts for a 5x5 inch card, and 25 watts for a 3x3 inch card.

Wicks Play Important Role

The wicks in the Hughes design provide the capillary pumping capability for fluid circulation, a path for condensate return to the evaporator, and a thermal conductance path between the container wall and the liquid/vapor interface. Separate types of wicks are used for the evaporator/condenser areas and for fluid flow, the later being an "artery" wick. The evaporator/condenser wicks keep the temperature drops in these areas low. Some capillary flow capability is also required. Since the flow paths from the artery wicks to the evaporator/condenser areas are very short, high flow performance is not required in these wicks.

Various materials for wick fabrication were investigated:

- Stainless steel screen
- Copper fletmetal
- Sintered stainless steels (Dynalloy X-7 and X-11)

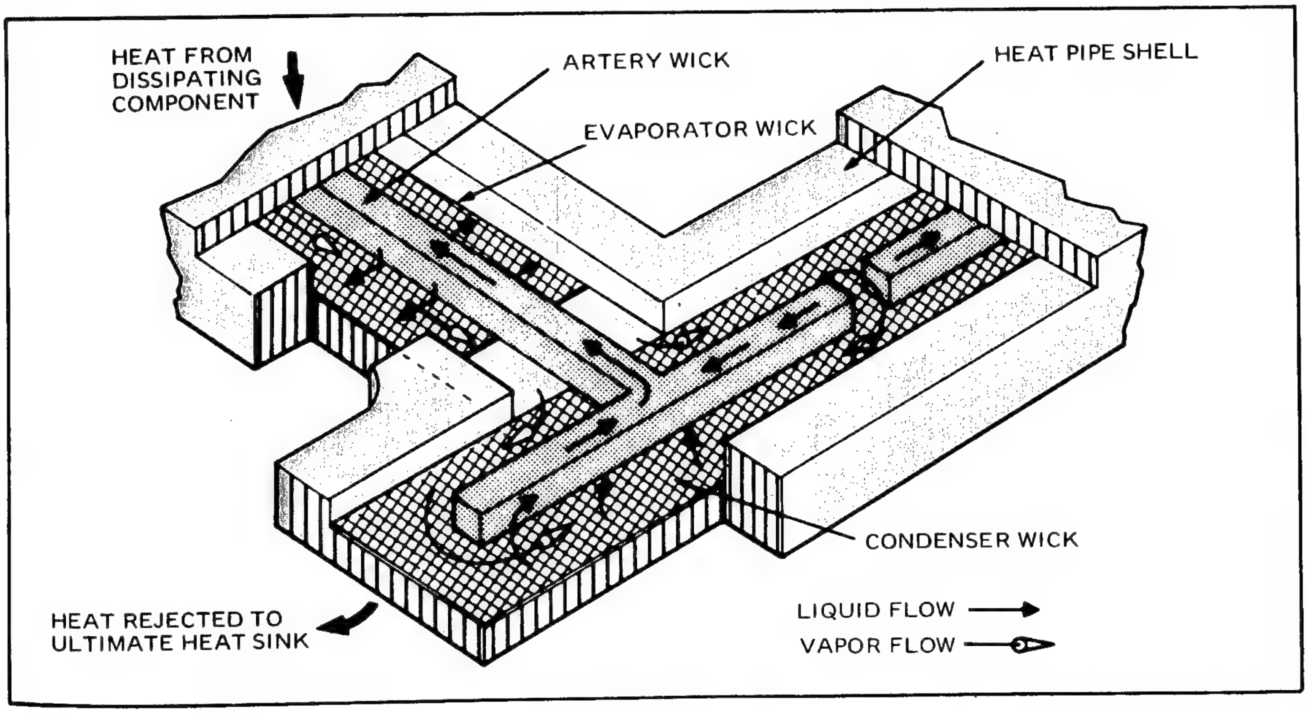


Figure 4

- Aluminum screens
- Sintered stainless powder.

Following a preliminary evaluation of these materials, tests were run on the stainless steel screen and sintered stainless metals (fibers). Because it has good capillary pumping action for heat transfer and can be brazed without being filled by braze alloy, Dynalloy X-11 sintered stainless steel fiber was finally selected.

Wick fabrication involves cutting the fiber to the proper shape, tack welding it into the pipe shell, and attaching it by brazing.

Brass Shells

From a large group of candidate materials, five—CDA 102 and 260 copper alloys, 303 and 347 stainless steel, and 6061 aluminum—appeared most suitable for fabrication of the heat pipe shells. Using a weighted rating analysis, these five materials were evaluated on the basis of:

- Thermal conductivity
- Brazing ability
- Structural strength and rigidity
- Machinability
- Chemical compatibility to the fill fluid
- Availability
- Compatibility with circuit card assembly process.

CDA 260 cartridge brass emerged as the best material for shell fabrication. Its nominal composition is 70 percent copper and 30 percent zinc.

Based on dimensional control and repeatability, labor cost, simplicity, process control, and tooling cost, Hughes selected die stamping and coining as the best technique

for fabricating the heat pipe shells. Other approaches were also highly rated and could be employed to good advantage by individual manufacturers based on their capabilities. These methods are numerically controlled routing and milling, die stamping and numerically controlled milling, and chemical milling.

Silver Braze Alloys Judged Best

The brazing alloy for shell construction (cover to base) had to be compatible with the close tolerance construction of the heat pipe and with the shell material. Other considerations in its selection included requirements for fluxless brazing compatibility with the fill fluid and wick, and hydrogen atmosphere. A final requirement was that the alloy have a lower brazing temperature than the wick to shell and cover brazes so that these bonds would not melt during the base to cover braze. Based on these criteria, Hughes selected H&H 560 (56% silver, 22% copper, 17% zinc, and 5% tin). The same alloy is used for temporary tack welds of the wick, cover, and base needed to facilitate handling.

Furnace Brazing Meets Needs

Furnace brazing, which lends itself to mass production techniques, was selected as the most viable process for joining heat pipes. Furnace brazed joints have excellent strength and seal properties, while the fusion of the metal and the grain structure of the joints produce a very reliable bond.

Because pipe interior cleanliness and freedom from pipe fluid reactive compounds are of prime importance, fluxless joining is mandatory. The use of a reducing atmosphere in a furnace provides the necessary cleaning action of a flux without producing residual slag. Hughes found a dry hydrogen atmosphere best for these conditions. Well designed fixturing and plate force loading techniques ensure good contact during brazing and proper fusion. Although the capital cost of this process is high, the mass production capability will keep process labor costs low.

Other joining techniques considered were electron beam welding, diffusion bonding, torch brazing, and soldering.

Fill System Designed

An important part of the manufacturing process is evacuation, filling, and sealing of the piping system. All feasible techniques were evaluated to determine the most effective approach for a production oriented system. The modified three way valve system shown schematically in Figure 5 offers the best performance of any of the systems tested. It has the lowest standard deviation as well as the quickest pumpdown time. This system is easier for an operator to handle than a bellows valve systems, which was also evaluated, since there are fewer valves to open and close. Consequently, Hughes designed and built a ten station evacuation, fill, and seal system based on the modified three way valve approach. (The schematic drawing shows just two of the ten stations.)

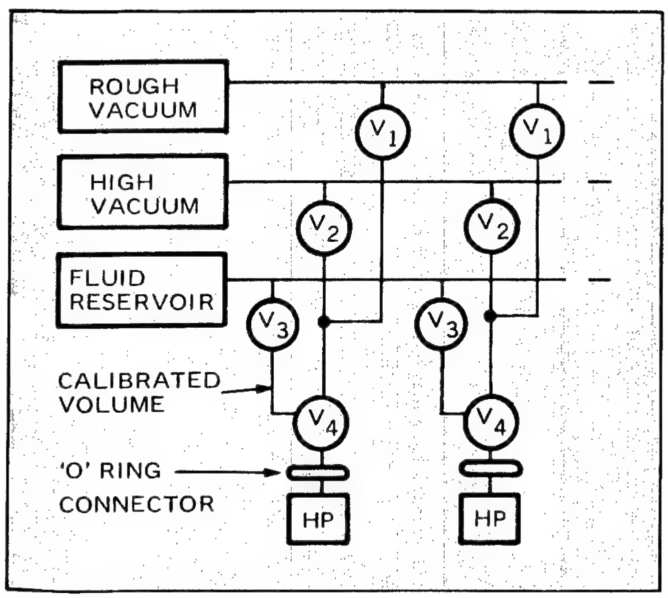


Figure 5

Heat Pipe Attachment

The Hughes designed circuit card heat pipe is directly compatible with the thermal mounting plate heat transfer techniques used on conduction cooled circuit cards, which

are used by Hughes for densely packaged electronic components. The heat dissipating electronic components are mounted on thermal plates that provide a low thermal resistance from the component to the heat sink. Aluminum, copper, or heat pipe thermal mounting plates can be used, depending on the system requirements. Aluminum thermal mounting plates are used at comparatively low power levels, copper plates at intermediate levels, and heat pipe thermal mounting plates at high power densities. The heat pipe thermal mounting plates have an additional advantage in that they provide uniform cooling of all components regardless of relative location on the thermal mounting plate.

The conduction cooled circuit card assembly using a circuit card heat pipe (Figure 6) includes the heat pipe, a ground bus bar, and a power bus bar, in addition to the printed circuit board and components. The insulated ground and power bus bars are mounted under the heat pipe with tabs extending beyond the heat pipe for connection to the printed circuit. Assembly of the conduction cooled circuit card utilizing a heat pipe involves

- Soldering the ground bus bar (4 mil copper with 0.1 mil tin plate) to the heat pipe.
- Bonding the power bus bar (4 mil copper with 0.1 mil tin plate) to the heat pipe with a fiberglass-epoxy insulator that also acts as the adhesive.
- Bonding the heat pipe assembly to the printed circuit board using a nomex-acrylic adhesive that also acts as an insulator between the power bus bar and the printed circuit.
- Bonding the electronic components to the heat pipe for heat sinking and mechanical strength. Flatpacks, dual in-line packs, or other component packages that have flat mounting surfaces are bonded to the heat pipe with a filled epoxy film adhesive. High-viscosity filled epoxy adhesive is used for resistors and an anaerobic cyanoacrylate adhesive for transistors in T0-5 and T0-18 cases. After components are bonded to the heat pipe, the component leads are soldered to the printed circuit.

The configuration of the circuit card heat pipe is not limited to the simplified geometry discussed here, but can be tailored to accommodate various circuit card layouts. Hughes has assembled thousands of heat sink circuit boards using this technique. It is cost effective and readily lends itself to single or multiple heat pipe circuit card assembly.

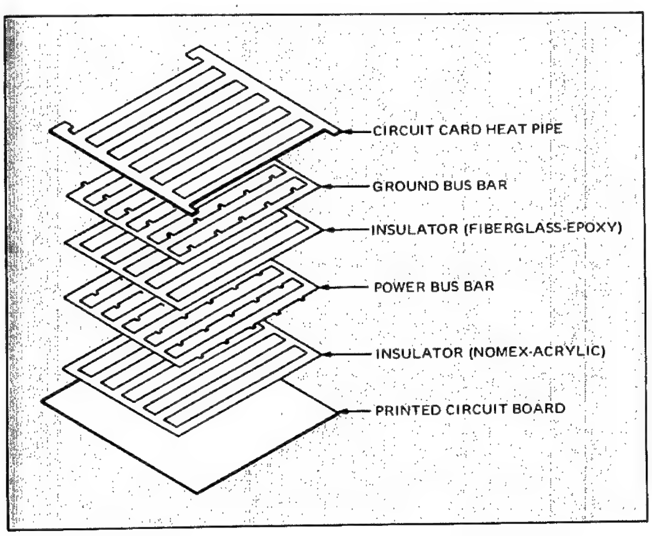


Figure 6

High Capacity Production

Using the materials and manufacturing methods selected during development of the heat pipe circuit card, Hughes designed a production facility that can evacuate, fill, and seal heat pipes at the rate of fifty per hour, producing four thousand per week. There are sixteen basic steps in the process, which requires about twenty-eight hundred square feet of floor space. Based on mass production techniques, the system is designed to provide the shortest transportation distance possible between processes. The system uses semiautomatic equipment as much as possible and in some cases modification to fully automatic equipment is possible. Such modification would further increase capacity and reduce unit cost, but would also increase capital equipment costs. Industrial engineering analysis would be required to justify any move to greater automation.

CAD/CAM of Dies

Forging, Rolling, Extrusion Applications

TAYLAN ALTAN is a Senior Research Leader, Engineering & Manufacturing Technology Department at Battelle in Columbus, Ohio. Dr. Altan worked between 1966 and 1968 at Dupont on research related to manufacturing of nonmelt processable plastics. Since joining Battelle-Columbus in 1968, he conducted and supervised research in many fields of metal forming. Dr. Altan has coauthored a book on forging and published more than 70 technical papers related to manufacturing processes. He has spent several years in various European countries and has maintained close personal contact with researchers of European universities and research laboratories active in manufacturing technology. At present, Dr. Altan is active in the ASME (Chairman of the Production Division in 1976), ASM (Chairman of the Forging and Swaging Activity since 1978), SME, and CIRP (International Production Engineering Research Institute)—Full Member since 1979. Dr. Altan's other past and present activities include Chairmanship of the Organizing Committee and Editor of the Proceedings of NAMRC—IV, Fourth North American Metalworking Research Conference, 1976; Adjunct Professor, Department of Industrial and Systems Engineering, Ohio State University, Columbus, Ohio.

CAD/CAM streamlined dies have been shown to be 13 percent more efficient than conventionally produced dies. This is the conclusion drawn from studies by Battelle's Columbus Laboratories sponsored by AMMRC, AVRADCOM, and ARRADCOM, which consistently show that computer designed streamlined dies produce good quality parts coupled with a smoother manufacturing process.

At present, the engineering design of metalforming dies requires complex information on metalflow, material properties, friction at die/material interface, and stresses on dies. Using this information along with appropriate methods of analysis, die geometries are defined either mathematically or as geometric entities which can be expressed in mathematical terms suitable for computer applications. Using interactive computer graphics, the newly designed geometry is displayed on a cathode ray tube (CRT) graphic display terminal to enable the die designer to review the accuracy and acceptability of the new designs. Acceptable die geometries, which are usually quite complex, are then manufactured by NC machining.

FORTRAN Standard Used

For interactive graphics work, Battelle Columbus Laboratories' computer aided manufacturing (CAM) group uses two major hardware systems:

- CDC-6500 computer with several Tektronix 4014 and 4012 direct view storage tube displays
- Digital Equipment Corporation (DEC) PDP-11/40 minicomputer with GT-40 refresh display and a light pen.

Both of these computer systems have FORTRAN compatible software to support the graphics hardware. Software developed for the CDC-6500 can be used to produce motion pictures, display and manipulate 3-D images, and produce dimensionless mechanical drawings. The PDP-11/40 is also equipped with an analog and digital input/output system for data acquisition and control purposes. A digital PDP-8E minicomputer is interfaced to a Bridgeport milling machine to provide four axis contouring capability. Numerical data can be keyboarded into this CNC system by the operator. The system also accepts NC tapes prepared by different programming languages, including APT (Automatically Programmed Tools). A postprocessor coded at Battelle can convert the output of these programs into a tape to be read by the CNC system. The postprocessor can also generate plan, elevation, and isometric views of the cutter paths to preview the accuracy of the results.

Although Battelle's CAD/CAM metal processing systems are developed on available CDC or DEC hardware, the design portions of the programs are written in standard FORTRAN. Thus, these CAD/CAM systems can be transferred with relative ease into other computer hardware equipped with graphics terminal and software.

Forging Systems Available

Four major CAD/CAM systems at various stages of development are available for forging applications: (1) aircraft structurals, (2) track shoes and other complex forgings, (3) blades and airfoils, and (4) round/axisymmetric forgings.

Two programs on forging structurals were conducted under the sponsorship of the Manufacturing Technology

NOTE: This manufacturing technology project that was conducted by Battelle Memorial Institute was partially funded by U.S. Army Commands under the overall direction of the U.S. Army Office of Manufacturing Technology, DARCOM. The AMMRC and ARRADCOM Project Engineers are Mr. Roger Gagne, Mr. Fee Lee, and Mr. Leonard Liuzzi.

Speeds Processing

Division of the Air Force Materials Laboratory. The first program had the objective of developing methods for CAD/CAM of the finisher and blocker dies for conventional forging of aircraft structural shapes. The second program had a similar objective with the application to isothermal forging of titanium alloys. Both programs were conducted in cooperation with a forging company and an aircraft manufacturer. The results of these programs have been consolidated in the form of an interactive CAD/CAM system called DIEFRG, which uses a graphics terminal to utilize the benefits of valuable design experience.

Starting with a set of coordinate data describing the various cross sections of the forging, DIEFRG processes, analyzes, and designs blocker cross sections to the specifications of the designer. If the read-in coordinate data are for a machined part cross section instead of a forging cross section, a forging section can be readily designed by prescribing the machining allowance and the draft angle. After adding the machining allowance and the draft angle to the machined part section, the computerized forging design procedure also modifies hard to forge deep holes and tall ribs.

The blocker design starts with the display of the cross section. The designer is requested to input design parameters. Although input data are necessary to obtain a specific design, stored default values can also provide a design which in many cases can serve as a start. The designed blocker shape is displayed along with the original cross section. The system can also display the dies at various stroke positions and can also zoom the display, allowing examination of details of the die and blocker sections (See Figure 1). After the blocker design, using given data on flow stress and friction, DIEFRG calculates the stress distribution as shown in Figure 2, the expected forging load, and other parameters such as cross sectional area, part volume, the plan area of die cavity, and the average forging pressure and flash dimensions. A major advantage of the computer aided design over the conventional procedure is the quick, reliable, and very accurate volume calculation. In addition, the computer can generate alternate designs almost instantaneously and without much additional effort. Despite these advantages, the designer must still make the final selection of the best suited design from a variety of available alternatives, which are obtained by changing one or more input variables.

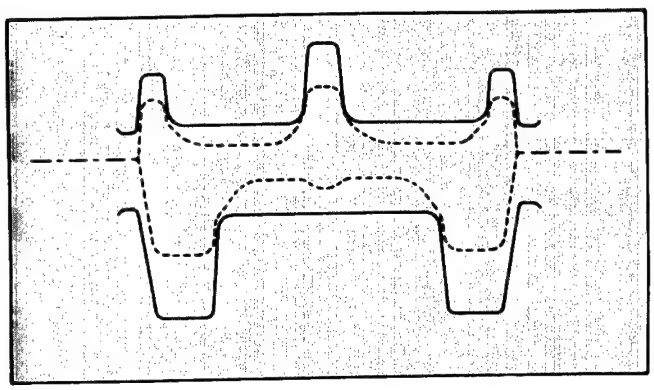


Figure 1

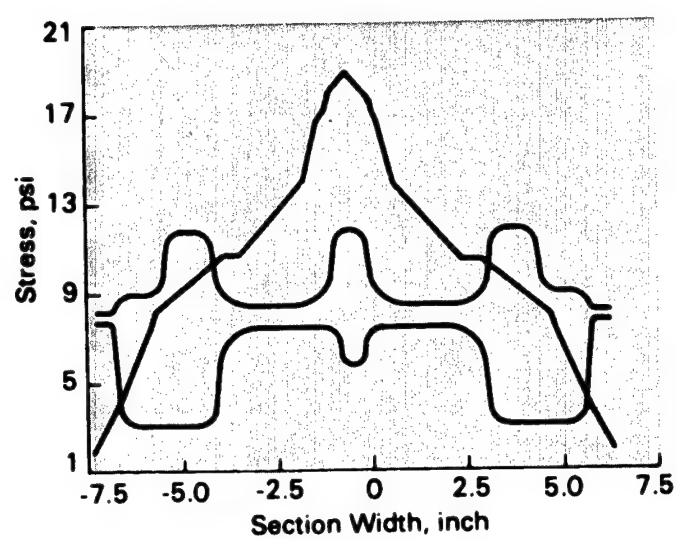


Figure 2

Track Shoes Developed

A study was recently sponsored by the Army Materials and Mechanics Research Center to assist in the production of tooling for track shoes for military crawler vehicles. The result of the program was a system of programs, called TRACKS, able to design the forging dies for such complex parts. TRACKS is totally interactive. The system requires that it be used by an experienced designer. It does, however, greatly increase his productivity by

allowing him to evaluate a number of alternatives in a fraction of the time now required. TRACKS has been implemented on a stand alone PDP-11/40 minicomputer system equipped with a refresh graphics display and light pen (See Figure 3).

Starting with a file of the coordinates describing each cross section of the forging, the system calculates the geometric properties (area, volume, centroid, etc.) of each section.

Under designer instructions, the system can then calculate the forging stresses, the average forging pressure, the center and the magnitude of load and the flash dimensions. Subsequently, the preform or blocker design is carried out. One of the features of the preform design module is the option which allows the designer to freely move the preform image relative to the die images. Using the light pen and a tracking cross, the designer may separate the images of the upper and lower dies, and then position the image of the preform so that it just nests into the dies. In this way, the designer can readily visualize how the preform will physically fit the finish die just before the finish impression is made. When load analysis and preform design have been completed for all sections, the CAM phase of TRACKS is used to prepare a tape for NC machining a model of EDM electrode of the preform.

Figure 3

Turbine and Compressor Blades Forged

As part of the Air Force sponsored program on CAD/CAM of forging dies, a system of computer programs called BLDFORG was developed to automate the design and manufacture of dies for forging turbine and compressor blades. The software was implemented on CDC-6000 series computers as an interactive system using direct view storage tubes. Capabilities of this system include

- Display and modification of input geometry
- Addition of flash geometry and forging envelope
- Determination of optimum forge plane
- Analysis of loads and stress history on the die surfaces during forging
- Display of load and stress history on the die surfaces during forging
- Simulation of the forging process
- Display of mental deformation
- Determination of optimum flash
- Determination of ideal preform and the optimum location of preform in the lower die cavity.

All displays are two or three dimensional. Both perspective and orthogonal projections are available at the option of the user. Other display options include (1) rotation of the blade geometry in space to any orientation, (2) selection and zoom of a portion of the blade geometry, and (3) display of hardware characteristics and the window size. The user has complete control over the display.

NC machining of dies or of the electrodes for EDM follows the CAD phase performed by BLDFORG. A special purpose program, BLDSURF, was developed to calculate the cutter location points for airfoils. An improved version of the BLDFORG system has been applied to Ti-6A1-4V compressor blades, shown in Figure 4 and is now being used by a large manufacturer for making dies to precision forge steam turbine blades.

Round Parts Studied

Two fundamental studies sponsored by NSF and AFOSR were aimed at developing a basic understanding of the behavior of metals and at determining quantitative relations between forging process variables and microstructure and mechanical properties of alloys.

In these studies, modular upper bound velocity fields have been developed and programmed to simulate the metal flow in compression of rings and cylinders. These programs allow the determination of velocity, strain,

Figure 4

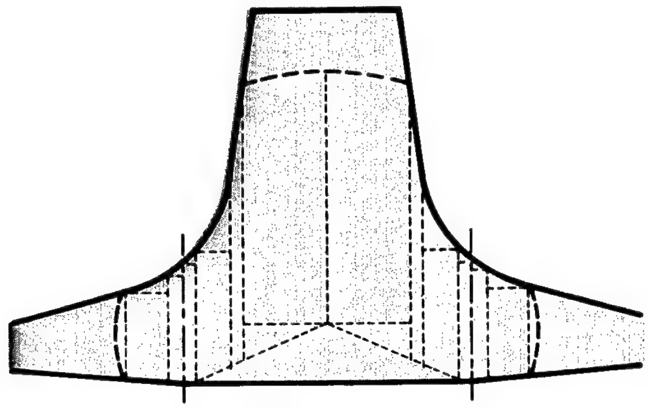


Figure 5

and strain rate distributions at each stage of deformation during compression. In connection with experimental ring compression tests, these programs can be used to estimate friction conditions and material flow stress in forging by developing calibration curves. The computer programs simulating the compression of a cylinder allow the prediction of metal flow and temperature distributions for various upset forging conditions. These programs have been successfully used to predict the effects of forging speed and lubrication on the temperatures at both the surface and the interior of a compressed cylinder or ring.

Interactive computer programs have also been developed for simulating the flow in forging round parts having a flange and shaft type configuration. The simulation technique is capable of predicting the metal flow (including bulging of free surface for simple round parts) during the entire forging process. Thus, the velocity, strain, and strain rate distributions, as well as approximate temperatures, are predicted during deformation (See Figure 5). This information is helpful in conducting fundamental studies for correlating process variables with product microstructure and properties.

Steel and Titanium Extruded

In a project conducted under AMMRC and AVRAD—COM sponsorship, computer aided techniques were developed for the design and manufacture of "streamlined" dies for the extrusion of shapes from steels, titanium, and other high temperature alloys. These dies provide a smooth metal flow from a circular container, or billet, to the shaped die exit.

The design of a "streamlined" die for extruding a "T" shape from a round billet is schematically illustrated in Figure 6. The geometry of this die and the variables of the extrusion process are optimized to (1) give a defect free extrusion requiring minimum postextrusion operations (twisting and straightening), (2) require minimum load and energy, and (3) yield maximum throughput at minimum cost. The process variables to be selected are the speed of the operation, the die geometry, the temperatures of the material and the die, and the frictional conditions at the container/die interface. For this purpose, a numerical method was developed and a system of computer programs called SHAPE was written for batch and interactive modes.

The surface of a "streamlined" die is defined as an array of points. The practical method of manufacturing this die is to NC machine a carbon electrode and then to EDM the die. For this purpose (and for a milling cutter of given radius), the coordinates of the cutter paths are determined as the cutter moves in a predetermined manner over the array of points defining the die surface. The computer programs developed for calculating the cutter paths contain special routines to check for undercutting and gouging. Dies for the lubricated extrusion of titanium and steel have been designed and manufactured by these CAD/CAM techniques and successfully used in extrusion applications.

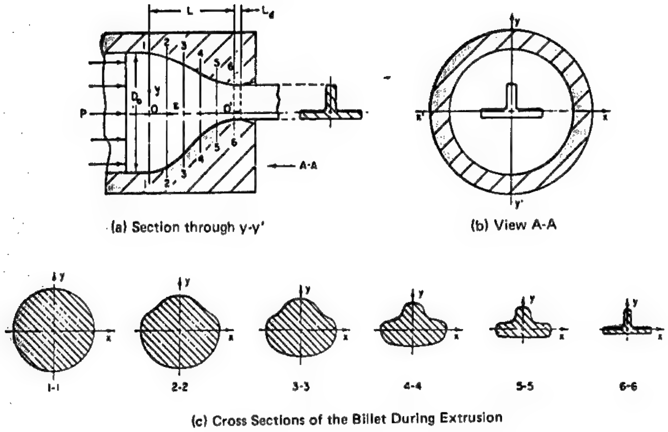


Figure 6

Dies for Aluminum Developed

As part of the CAD/CAM extrusion project, an interactive system of computer programs called ALEXTR and EXTCAM were developed for the design and manufacture of dies for extruding aluminum structural shapes. ALEXTR assists the designer in determining (1) the optimum number of openings to have in a die, (2) the location of the openings in the die, (3) the stresses in the die and support tools, (4) the compensation of the die openings for deflection under load, (5) the bearing dimensions for balanced metal flow, and (6) the thermal shrinkage of the extrusion and thinning during stretching.

After the die design is completed, the NC machining program, called EXTCAM, takes the designed dimensions for the die opening(s) and generates the cutter paths and an NC tape for manufacturing the die. Extcam produces NC tapes for (1) machining the template for the finished extrusion, (2) machining the die template or front EDM electrode, (3) machining the die opening from front or back directly into the die, and (4) machining the die bearings from the back side of the die. The size of the cutter to be used is specified by the user.

Rods and Tubes Extruded

In extrusion, metal flow and temperatures are interdependent and they influence the properties and the tolerances of the extruded product, as well as the economics of the extrusion process. Under internally sponsored research projects, Battelle has developed a set of computer programs for simulating the kinematic and thermal conditions in axisymmetric (round) deformation processes, specifically, in extrusion.

The calculation of metal flow and temperatures in extrusion involves the complex problem of determining (1) a velocity field and (2) simultaneous heat transport and heat transfer. Therefore, in these computer programs an approximate computerized numerical method is used. This method determines the metal flow with upper bound analysis and approximates the heat generation and the simultaneous heat transfer as taking place in two consecutive steps. The heat generation and heat transport take place at the beginning of a time interval, Δt, associated with a small step of deformation. Then the heat transfer takes place as for a stationary medium during Δt. The repetition of these two steps simulates numerically the deformation process and gives the temperature distribution as a function of time. This procedure has been applied to simulate and to calculate the temperatures in many axisymmetric deformation processes such as compression forging, ring forging, wire drawing and extrusion of rods and tubes.

Strip Rolling Process Formulated

A system for computer aided simulation of the strip rolling process was developed by combining the best available analyses of the process with a newly developed finite difference method for predicting time dependent temperatures in the strip and the work rolls during rolling. Under this study two mathematical models were developed for predicting the significant variables of the strip rolling process.

The first model and the associated computer program ROLLING estimates the roll separating force and the roll torque. This includes the most advanced/recent analyses of (1) the plastic deformation zone under the rolls, (2) the elastic compression and recovery zones in the strip, and (3) the elastic flattening of the work rolls. The final solution is obtained by an iterative process until the calculated roll pressure distribution is compatible with the elastically deformed arc of contact on the rolls.

The second model and the associated computer program ROLTEM simulates metal flow and calculates temperatures in the strip during rolling. Temperatures in strip rolling are calculated by taking into account simultaneously the heat generation due to deformation and friction and the heat transfer. For this purpose, the metal flow is described by an upper bound velocity field, and the heat transfer calculations are performed using a finite difference method.

Plate Rolling Process

An understanding of the plate rolling process is essential to obtain an optimum rolling schedule for plates without exceeding the capacities of the available rolling mill installation, while at the same time meeting metallurgical and mechanical specifications of the rolled plates. In particular, the knowledge of how the material is going to spread during a pass, and the estimates of rolling torque and load per pass is essential in the scheduling of roll passes and in controlling the overall dimensions of the rolled plates.

The upper bound method of analysis is used to predict metal flow, and the slab method of analysis is used to predict stresses, loads, and roll torque. The computer program, PLTROL, is operational on an interactive mode with graphics capability and can be used for simulation and process optimization.

Gun Barrel Forging Examined

The success of the radial forging process for large caliber gun barrels, as shown by a study for the Watervliet Arsenal, often depends upon the appropriate die design and selection of machine variables. Therefore, it is necessary to predict the effects of die, machine, and process variables upon the success of the operation and the properties of the product. For this purpose, metal flow analyses and a computer program, called RADFRG, were developed. RADFRG can (1) determine the metal flow, strain rates, strains, and deformation energy; (2) predict deformation loads for forging with single angle and compound angle dies; (3) predict temperature variations due to deformation and heat transfer during forging; and (4) optimize the overall process in terms of using the minimum amount of energy to obtain the maximum productivity. The program RADFRG is now being utilized for optimizing the manufacturing process for cold, warm, and hot forging of gun barrels by radial forging.

Traditionally, small caliber gun barrels (below 40 mm bore) are forged to smooth bore and the riflings are then machined by broaching. An alternative and potentially less expensive method of manufacture is to cold form the rifling by radial forging or swaging over a profiled mandrel. However, obtaining a precise definition of the rifling shape by radial forging requires a precise design and control of the process.

To investigate and optimize this process, ARRADCOM sponsored development of an interactive computer aided model for predicting the relationships between the cavity fill and the forming forces. In developing this computer model, a simplified configuration of the die/workpiece combination was considered. Initially, large scale experiments were conducted to investigate the metal flow near the fillet and corner radii of the rifling cavity. Subsequently, the results of these experiments were used to develop a modular and computerized upperbound technique to simulate metal flow. The computer predictions were compared with experimental results and good agreement between both results were obtained.

Shells Formed

Another ARRADCOM program studied the design of the nosing process for producing artillery shells. The nosing of the rough machined shell is accomplished by forcing a contoured die axially over the open end of the shell, which is usually preheated, while the body of the shell is supported by a chuck. In this project, analytical techniques and the associated interactive computer program, NOSING, were developed for determining the optimum combination of the process variables for defect free nosing of shells, both hot and cold. The program NOSING determines (1) the temperature distribution in the shell wall after induction heating, (2) the load stroke curve for the nosing operation, (3) the conditions under which buckling on the wall may occur, and (4) the effect of ram speed upon nosing load, metal flow, and buckling.

Other Uses

Additional CAD/CAM die technology has been applied to the tandem drawing of shells and sheet metal forming operations.

Acknowledgments

The CAD/CAM systems summarized in this paper were developed under various Air Force, Army, and NASA sponsored programs. This support is gratefully acknowledged. The development work was conducted by some members of Battelle's CAM group, as follows: Dr. Nuri Akgerman (Forging, Rolling, NC machining), Mr. Carl Billhardt (Forging, Extrusion, NC machining), Dr. Goverdhan Lahoti (Extrusion, Sheet Metal Forming), Dr. So Ik Oh (Sheet Metal Forming, Rolling, Compression), Dr. Pal Raghupathi (Radial Forging, Deep Drawing, Rubber Forming), and Dr. Mani Subramanian (Forging, Forming of Shell, Sheet Metal Forming).

Process Development Speeds P/M

Computer Aided Design of Preforms

HOWARD A. KUHN is Professor of Metallurgical and Materials Engineering and also Professor of Mechanical Engineering at the University of Pittsburgh. Prior to joining the Pittsburgh faculty in 1975, Dr. Kuhn was Professor of Metallurgical Engineering for eight years at Drexel University in Philadelphia after teaching Mechanical Engineering for a year at Carnegie-Mellon University in Pittsburgh. He received his Ph.D. degree in Mechanical Engineering in 1966 from Carnegie—Mellon after earlier obtaining M.S. and B.S. degrees in M.E. there. Besides instituting metalworking courses and laboratories at Drexel and Pittsburgh Universities, Dr. Kuhn has conducted sponsored research in fracture during metalworking processes and powder forging and has served as consultant to industry on development of popular forging processes and on defect problems in metalworking processes.

No Photo Available

A program for computer aided design (CAD) of powder metal forging preforms written at the University of Pittsburgh should end most of the trial and error labor involved in developing acceptable preforms for complex parts. Developed for the Army under direction of Rock Island Arsenal, the program has been successfully applied to selected military components. Program output specifies preform shape and dimensions that will avoid defects and ensure full density in the forged part.

Because the complexities of metal flow still preclude exact definition of preform shape, some minor preform adjustments may be necessary after a few forging trials. But, compared with the usual trial and error design procedures—which become the rate limiting step in development of powder metal forging processes—these adjustments will be negligible. As the program evolves through user experience and increased understanding of metal flow mechanisms, its accuracy and predictive capability will steadily improve and the need for such adjustments will decline.

Powder metal forging preforms for complex shapes must provide a delicate balance between limits on deformation. There must be sufficient deformation to ensure densification and structural integrity but not so much that cracking results. The CAD system makes results of past experience in achieving this balance available to any user, eliminating the usual tedious procedures. The program uses a part geometry module, a preform design module, and a preform display module. User inputs to initiate the program are the finished component profile, the forging direction, and the desired minimum amount of lateral flow. The program calculates dimensions and volumes of each characteristic region of the part, evaluates preform shape, and then calculates overall dimensions and displays the desired preform shape.

Preform Design Vital

Preform design is of vital importance in powder metal forging because of the need for nearly full density to obtain tensile strengths comparable to those of wrought materials. For critical, high strength applications, acceptable impact and fatigue resistance are achieved only

NOTE: This manufacturing technology project that was conducted by the University of Pittsburgh was funded by the U.S. Army Armament Materiel Readiness Command under the overall direction of the U.S. Army Office of Manufacturing Technology, DARCOM. The ARRCOM Project Engineers are Mr. R. W. Kalkan (309) 794-5504 and Mr. Mukesh Solanki (309) 794-6198.

if residual porosity is eliminated and densification is accompanied by some degree of lateral flow. Thus, metal flow during forging must be sufficient to fill all regions of the die and to simultaneously densify the material completely. The metal flow determines the vital balance between deformation limits.

Proper control of metal flow is needed for uniform densification and for elimination of localized stress and strain states that can cause defects. It is exercised through proper selection of process parameters such as die design, lubrication, temperature, and preform shape. Preform design provides the greatest control. In most cases, changes in preform shape or dimensions can alter metal flow sufficiently to produce a fully dense part without defects. Preform design, then, is the key step in successful powder forging.

Using The Computer

Design of a powder metal forging preform to meet these needs requires knowledge of the densification, flow, and fracture behavior of the material and of the effects of die design, lubrication, and temperature on this behavior. For complex shapes, preform design involves time consuming trial and error design, using only previous experience to prescribe an initial estimate of the proper shape.

One approach to this problem involves subdivision of a complex component into elementary zones of deformation. Workability and densification analysis then is applied to each zone to determine the preform shape that will lead to full density without fracture. This general approach was computerized using interactive graphics to develop the CAD system described here.

Precise input of complex three dimensional shapes, however, is very difficult and complicated—so much so that the intended time savings of CAD could easily be lost. Therefore, a simplified input procedure is used. A dominant profile or plane of symmetry is first chosen to give the basic two dimensional features of the part. Then the features in the third dimension (perpendicular to the profile or symmetry plane) are input quantitatively. Next, the preform design logic system subdivides the profile into regions and develops the preform design for each region, reassembling and smoothing them into the overall preform design. This is exactly the way rational preform design is accomplished by experienced designers. The CAD program makes this experience available to any user.

Two Dimensional Commands Used

The program uses a simplified automatically programmed tool (APT) system. The APT program system was developed to transmit information from an engineering drawing to the computer and is used extensively in numerically controlled machining. The part geometry depicted by the engineering drawing is translated by the APT user into a sequence of statements defining the cutter paths and operations required to shape the part. Complex three dimensional geometries may be defined in this way, but extensive experience and programming skill is required on the part of the user.

In the CAD approach, the emphasis is on simplicity for widespread use, so the complex programming skills of three dimensional APT are not desirable. Furthermore, the requirement here for part description is to drive a graphic display rather than a cutting tool. Thus, a hybrid scheme was developed in which two dimensional part description commands are used that are based on three dimensional APT. This simplified APT system is used not only for part description but for description of upper and lower die profiles and for description of the preform shape. Furthermore, the system can be used interactively to change die or preform geometries.

Designing A Part

To illustrate the computer aided preform design procedure, let's consider a cartridge guide ramp for the M85—for which a preform was designed using the CAD program. The part is shown in a photo in Figure 1 and in an isometric view (which is sectioned along a vertical plane of symmetry) in Figure 2.

In the CAD system, selection of the forging direction is a user function—one that requires some forging experi-

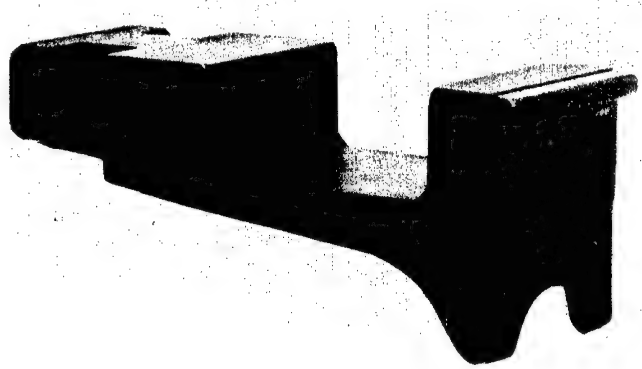


Figure 1

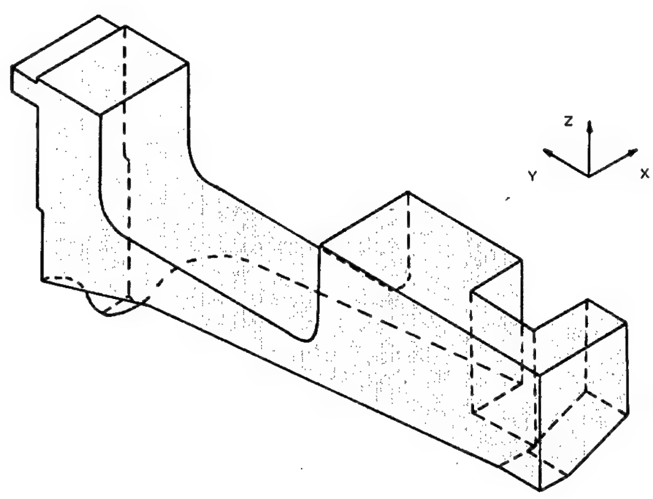


Figure 2

ence. Forging direction is generally dictated by the component shape. In the guide ramp, the X and Y directions (width and length) were eliminated from consideration because lugs and reentrant corners would prevent part ejection from the die. Their use, which would involve subsequent machining of the lugs, would be a last resort. Forging in the Z-direction (height), on the other hand, does not entail ejection difficulties and only the hole in the X-direction requires metal removal.

Metal Flow Direction Determined

With the forging direction thus established, the part was described in terms of the upper and lower punch profiles coupled with specified widths of each region of the part. Using the simplified APT system, the component geometry was entered for internal reconstruction and calculation of the volumes of each region. The end lug was input by entering the end profile (XZ-plane) and depth in the Y-direction. The internal division of the part into regions and the volume of each region are given in Figure 3.

Once inputs were made, the first design step was to determine the direction of metal flow. One option for the guide ramp would be to use a flat, unfeatured preform having the same plan profile (XY-plane) as the finished part and to form the vertical profiles by metal flow. This approach, however, would result in extensive metal

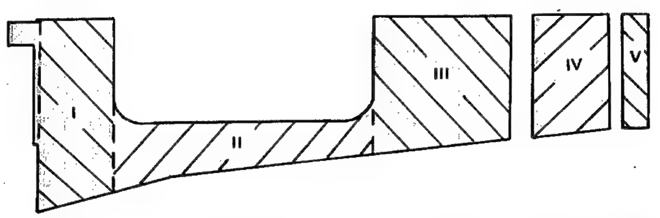


Figure 3

flow from Region 2 to Regions 1 and 3, with cracks forming at the top free surfaces of Regions 1 and 3 and around the fillet radii. In addition, extensive flow around the upper punch corners would lead to very high die wear in these areas. Since these limits are incorporated in the preform design program, the program rejected this option.

Multiple Options

Another option would be to fabricate the preform with the end regions (all but three) fully formed, allowing metal flow from these regions into Region 2. This would require an excessively thin preform section in Region 2; the preform design program rejected this option as well.

A final alternative would be to fabricate the preform so that its profile matched the profiles of the top and bottom punches (except for the lugs at the bottom of Region 1) and then allow lateral flow across the width to form the part details. Some vertical extrusion flow would be required to form the lugs at the bottom of Region 1. This option would entail very little risk of fracture because lateral flow across the width leads to comprehensive strain in the forging (Z) direction with little tensile strain along the length because of friction at the contact surfaces. Preform dimensions were determined so that the mass of metal in each region of the preform matched the corresponding region of the finished part. As a result, compression during forging in the forging direction leads to lateral flow across the width and no flow along the length. This method eliminates the possibility of die contact surface cracks caused by flow around the punch corners and was the one chosen by the CAD program.

Program Sets Widths

Once the preform concept and flow direction were established, the preform design program determined preform widths. These dimensions are dictated in each region by the mass of that region, the preform density, the height of each region in the finished part, and the amount of lateral flow permitted or desired across the width. Figure 4 shows the preform in contact with the upper and lower punch profiles at the first instant of contact. Broken lines indicate the die walls. The total stroke is the punch travel required for full densification and is the final adjustable parameter determined by the desired amount of lateral flow. For a typical region, the preform width is given by

$$X = V_o/\rho A$$

where V_o = volume of that region in the finished part
ρ = preform density
A = cross sectional area of preform

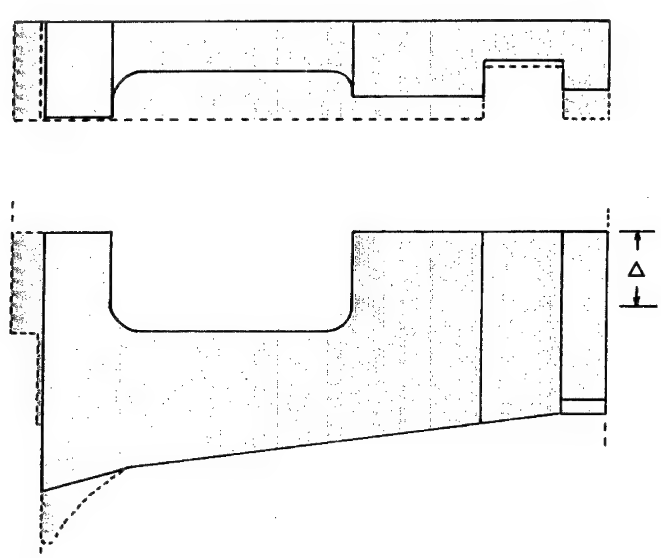


Figure 4

The preform cross sectional area increases with increasing height of the preform, i.e., increasing stroke, which decreases the preform width in that region. Thus, when a minimum desired amount of lateral spread is specified by the user, the preform width is calculated in the region where minimum lateral spread occurs, and the stroke is determined from the above equation. This in turn determines the preform width in each region. Sharp discontinuities in the preform are avoided by blending between regions.

The final preform shape displayed by the CAD program is that shown in Figure 4. Note that some extrusion flow is required to form the lugs in the lower left and a small amount of longitudinal flow is required to form the lug at the upper left. However, major metal flow is through the width. The total stroke is indicated by Δ .

Preform Advantages

There are several important features to recommend the resulting preform. Since each region has the required mass of the finished shape, densification problems are avoided. Die wear at the corners is avoided because there is no substantial flow around them. Free surface fracture is also inhibited by compression over the entire volume of the preform.

The clearances for all the regions in the part are computed for a stroke of 0.5 inch. This was explicitly chosen to allow for a small clearance in Region 3 to permit the preform to fall into the dies before forging.

The preform shown in Figure 4 will lead to lap defects due to the sharp transition in the profile from one region to another. Generous external blending prevents this defect. The blended preform is shown in Figure 5. The overall metal flow during forging is shown in Figure 6.

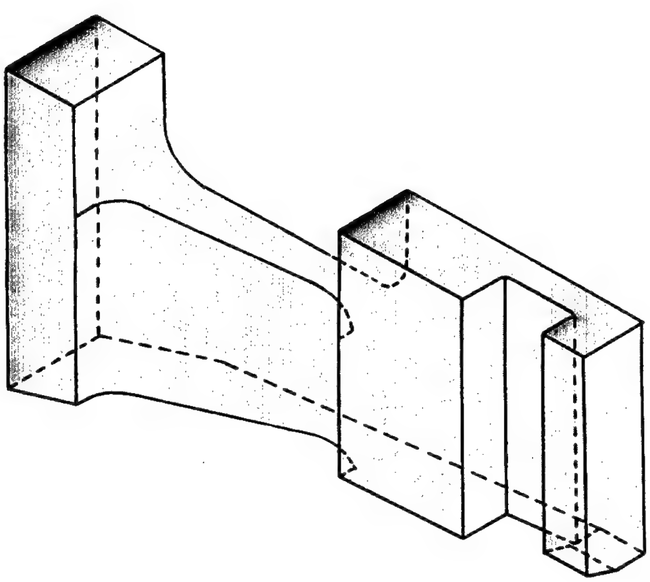


Figure 5

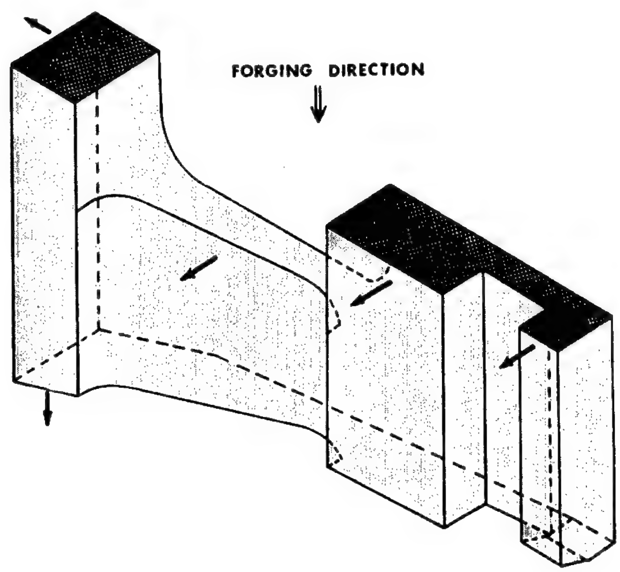


Figure 6

Trial Forgings

Six preforms were machined according to the preform drawing (Figure 7) using 4640 steel powder compacted to 80 percent density and sintered at 205 F. Each machined preform was coated with graphite, reheated to 1800 F, and forged in a hydraulic press at the Hoeganaes Corporation in Riverton, New Jersey. Prior to forging, graphite in water was sprayed onto the dies for lubrication.

Satisfactory forgings were obtained with no defects and lugs and lips fully formed. Macrographs taken at various sections indicated good densification, except for some residual porosity at the surfaces.

A flat preform also was forged to ascertain the defect formation. As expected, there were considerable fractures and lap defects. This experiment served to confirm the importance of preform design in powder forging.

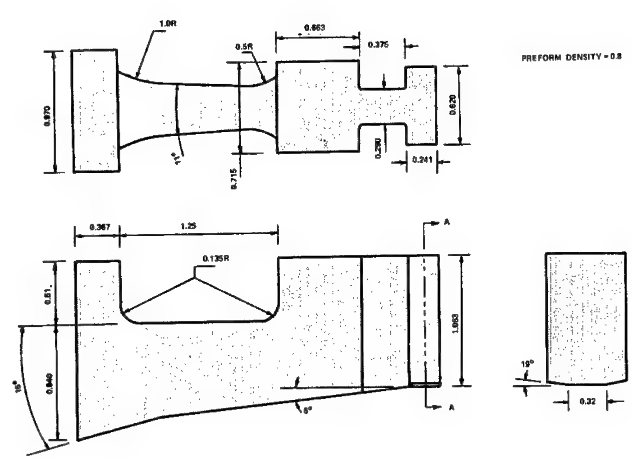


Figure 7

HIP Improves Castings

Manufacturing Cost Lowered

PETER G. BAILEY is Manager, Forging and Forming, Manufacturing Technology Operation, Aircraft Engine Group, General Electric Company, Cincinnati, Ohio. Since joining the General Electric Company, Mr. Bailey has worked in the Process Development area for superalloys. In his previous position as Manager of Premium Casting Development, he had the responsibility for developing and evaluating advanced fabrication techniques for superalloys. He was responsible for process development in the densification of castings, including a prior Air Force direct contract, "Process for High Integrity Castings", a just completed Air Force contract, "Manufacturing Methods for Low Cost Turbine Engine Components of Cast Superalloys", and in-house applications of the densification process. In addition, he was responsible for development of ODS alloys and fabrication techniques. Mr. Bailey joined the General Electric Company in 1972. Prior to that time, he was involved in the development of dispersion strengthened mill products with E. I. DuPont deNemours and Co. and then Fansteel, Inc. Prior to his DuPont-Fansteel experience, Mr. Bailey worked for the Linde Division of Union Carbide Corporation, primarily in the application of industrial gases to steelmaking. At DuPont and Fansteel he was intimately involved in the manufacture, evaluation, and application of TD Nickel, TD Nickel Chromium, and TD Cobalt alloys. He was Principal Investigator on three Air Force sponsored programs. Mr. Bailey obtained a B.S. in Mechanical Engineering from Cornell University and an M.S. in Metallurgy from Stevens Institute of Technology. He is a member of the American Society for Metals.

No Photo Available

WILBUR H. SCHWEIKERT is Manager, Casting Projects, Material Process Development Laboratories, General Electric's Aircraft Engine Group. He is the inventor of the system for nucleation of high nickel and cobalt alloys for making fine grain castings to improve fatigue life. He also invented a system for making an inert mold for casting titanium and other highly reactive metals. For the past five years he has been involved in Air Force Direct Contracts relating to Hot Isostatic Pressing (HIP) of various alloys to improve the mechanical properties of the materials such as is reported in this article. Mr. Schweikert joined General Electric Company in 1951 to coordinate critical materials utilization on the J47 engine and also directed materials selection and process development for a new engine which eventually became the current J79 engine. He developed a procedure for making thin high strength stress free compressor discs and initiated isothermal heat treatment of engine wheels, blades, shafts, etc., in development engines. Mr. Schweikert initiated the process for coring precision cast air cooled turbine buckets and vanes in the years 1956 to 1960 and has worked with the casting industry to develop the system now capable of making the very sophisticated cooling systems in use in current engines. He received his Aeronautical Engineering degree from Yale in 1943, then flew in the European Theater during World War Two. He later received engineering degrees from Cincinnati University in Metallurgy (1948) and Mechanics (1952). He is a Registered Professional Engineer in California.

No Photo Available

By applying hot isostatic pressing (HIP), General Electric has found they can replace machined forgings with net shape castings in the manufacture of aircraft components. The net result is lower manufacturing costs and improved part quality. Working on an Air Force contract, G. E. has integrated HIP densification into the casting process, improved mold systems and heat treatment, and refined alloy chemistry to realize substantial property improvements in cast Inconel 718. Subcontractors for the effort have been Battelle's Columbus Laboratories, Precision Castparts Corporation, and Anacast.

Weldments Reduced

G. E. sees a major potential use of the process in static structural castings that are presently machined from forged cylindrical "tubs" or weld fabricated from rolled rings and sheet. HIP will allow integration of horizontal flanges in these parts and consequent reduction in machining and welding costs. With the removal of welds from critical stress locations and the elimination of weld distortion, part quality will improve.

By applying HIP to cast parts, G. E. has obtained tensile properties near those of forgings and notched fatigue strength equal to that of forgings. Significant improvements in fatigue strength have also been noted in cast 17-4PH.

NOTE: This manufacturing technology project that was conducted by General Electric was funded by the U.S. Air Force Materials Laboratory. The AFML Project Engineer is Mr. Ken Kojola (513) 255-5151.

The property improvements obtained in cast Inconel 718 are attributed to the closure and healing of inherent small casting voids and to the nearly complete solution of the hard, brittle segregates that form during natural cooling of the casting. This improved homogenization both enhances mechanical properties and significantly improves weldability.

Part of Larger Effort

G. E.'s effort to apply HIP to castings forms a significant part of a comprehensive series of programs to improve and expand casting technology. The overall aim of the HIP effort is to expand the use of castings and to impact engine hardware costs by

- Reducing inherent casting costs through increased casting yield and compromises in casting practices (such as fewer gates) that are obtained by the application of hot isostatic pressing after casting.
- Improving the quality and properties of castings by HIP, so that expensive forged parts can be replaced with less expensive castings.
- Reducing HIP costs, for example, by decreasing cycle time or by combining HIP with alloy heat treatment.
- Reducing associated manufacturing costs, such as those for welding, chemical milling, and scrap loss.

The program thrust is toward process integration, as illustrated in Figure 1.

Process studies have been carried out using engine and airframe components currently produced by casting Inconel 718, 17-4PH, Ti-6Al-4V, and Al 357. The greatest progress has been made with Inconel 718 using the main mount casting shown in Figure 2. The effort has resulted in property improvements through HIP densification, chemistry, refinement, and development of high conductivity molds.

Densification and Homogenization

The use of HIP with cast Inconel 718 has produced promising improvements in cast mechanical properties. As noted, these improvements relate directly to the closure of shrinkage porosity and the homogenization of the alloy matrix. Homogenization of cast Inconel 718 is practically complete following a 2125 F HIP cycle. Although densification is obtained at temperatures as

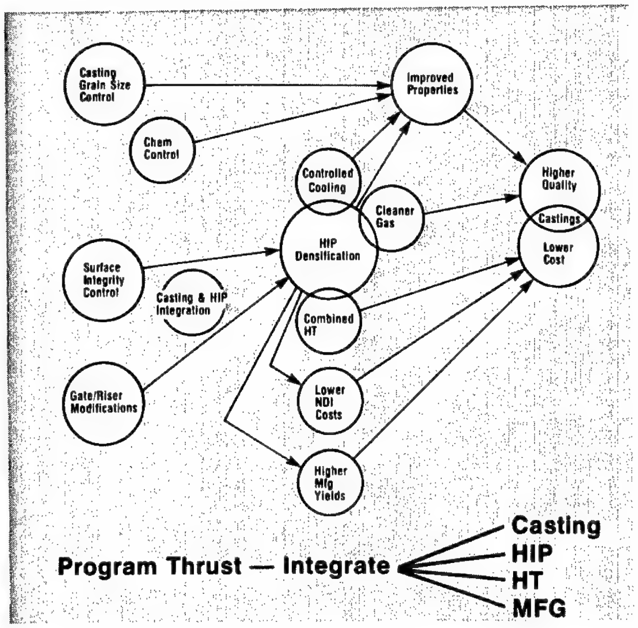


Figure 1

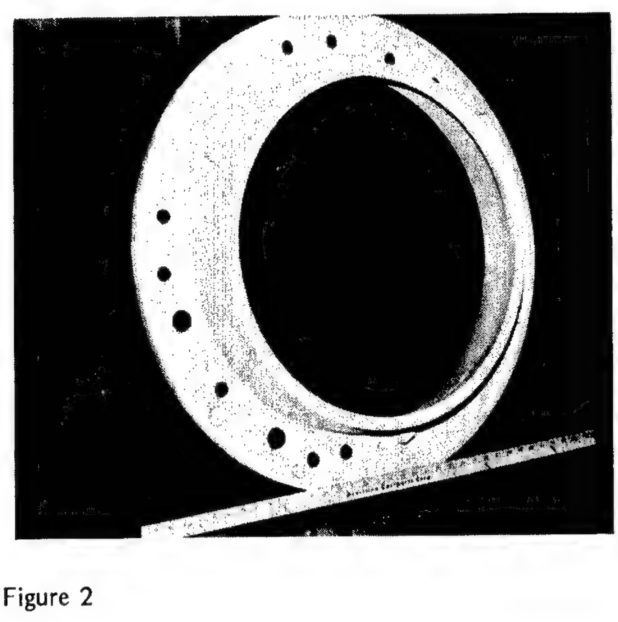


Figure 2

low as 1950 F at 15 ksi pressure, the higher temperature is required to complete homogenization. The homogenization produces a fine subgrain size within the as cast coarse grains which apparently enhances mechanical properties.

Tensile and fatigue strength improvements in cast Inconel 718 that has been hot isostatically pressed are shown in Figures 3 through 5. Of particular significance are the demonstrated improvements in tensile strength minimum values and in ductility. In notched low cycle fatigue tests at $K_t = 3.0$, HIP castings have also shown properties equivalent to those of forgings. This is a very important comparison for engine components, which operate at notch factors between 2.0 and 3.0. Significant improvement in the low cycle fatigue life of cast 17-4PH has also been achieved, as illustrated in Figure 6.

Chemistry Modification

Refinements in the existing Inconel 718 casting specification have resulted in castings with tensile strength very close to that of forgings, as shown in Figure 7. These results were achieved using the content ranges listed below. The most significant changes in the specification were increased columbium/tantalum and titanium levels and a lower aluminum content:

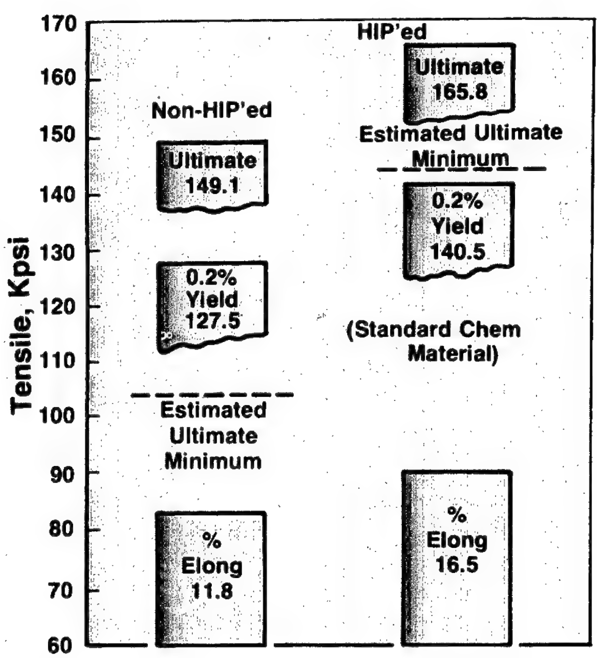


Figure 3

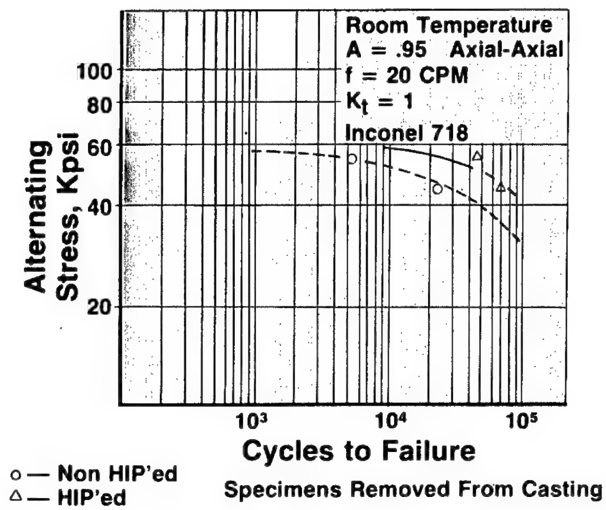


Figure 4

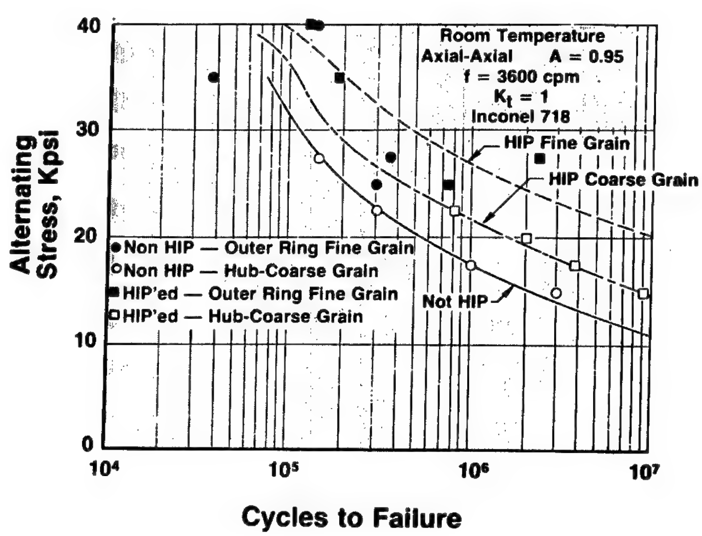


Figure 5

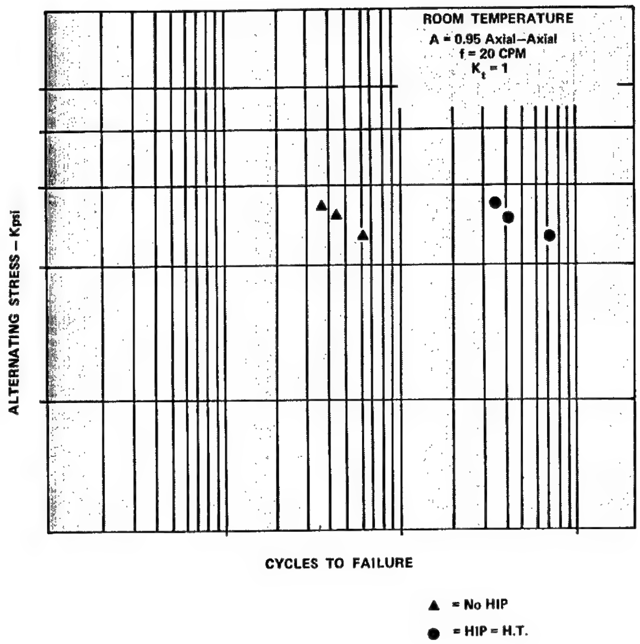


Figure 6

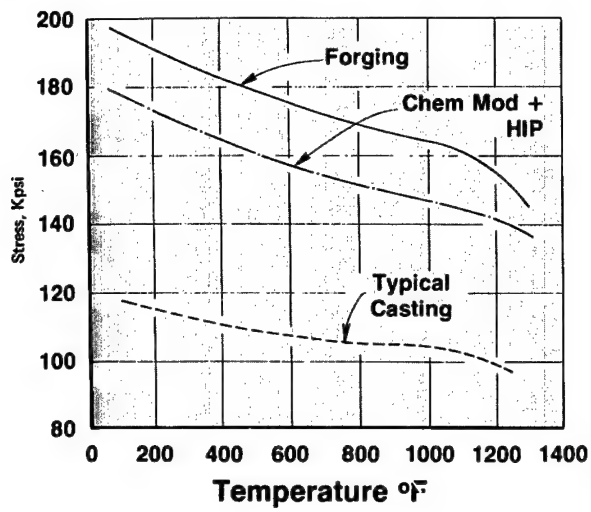


Figure 7

High Conductivity Molds

G. E. has also used high conductivity molds to improve cast properties. Reductions in grain size and interdendrite arm spacing are known to improve mechanical properties. As shown in Figure 8, rapid solidification will reduce the interdendrite spacing. The thermal conductivity of mold materials plays a major role in affecting solidification rates. The effect of increased mold conductivity on tensile properties is shown in Figure 9.

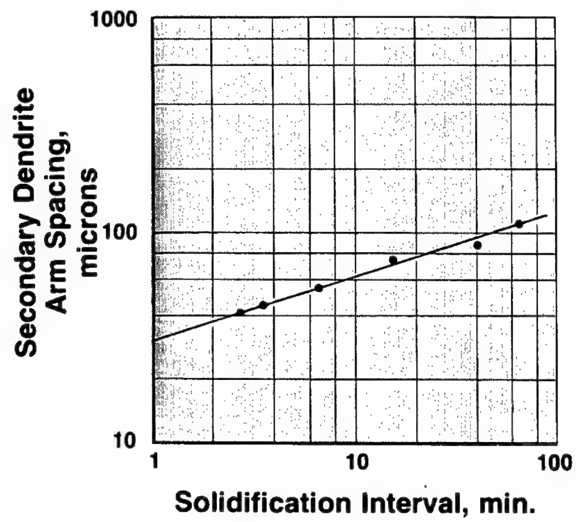


Figure 8

HIP Process Studies

G. E. has conducted a number of experiments to improve the HIP cycle itself. For example, they found that increases in the power input, combined with delayed but rapid pressurization, reduces HIP cycle time by two hours. They also performed a detailed gas analysis experiment to trace atmosphere changes occurring during a typical HIP cycle. The impurity levels and sampling conditions are summarized in Table 1. The first seven scans were made during heating and pressurization prior to HIP, while the last three were made during depressurization the following day. Below about 1200 psi, the gas entering the autoclave comes from storage tubes maintained at various pressures. The first two scans were made while equalizing the gas pressure in the autoclave with a storage tube maintained at 400 psi. The increase in oxygen, nitrogen, and moisture levels from Scan 1 to Scan 2 is attributed to heating, which drove off moisture and air trapped in the thermal barrier when it was out of the autoclave.

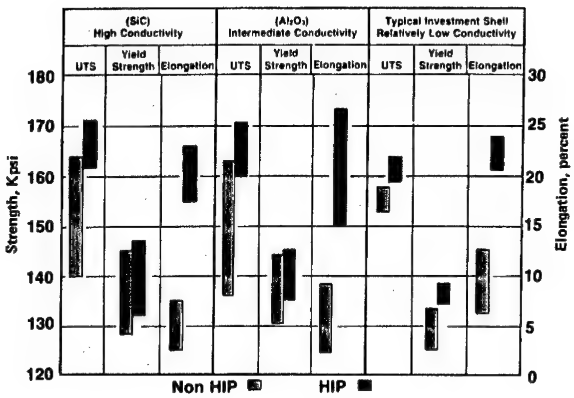


Figure 9

Scan No.	Autoclave Temp., C	Pressure, psi	HIP Gas Impurities, ppm			
			Hydrogen	Oxygen	Nitrogen	Moisture
1	64	375	595	73	259	63
2	142	390	593	233	797	127
3	333	400	601	405	1340	127
4	520	770	176	84	304	50
5	681	1000	2608	318	1138	56
6	940	2600	161	35	199	63
7	1000	4500	47	11	61	50
8	RT	3500	91	7	167	23
9	RT	2700	88	6	160	30
10	RT	2050	96	22	182	34

Table 1

Contaminant levels changed abruptly (Scans 3, 4, and 5) each time a different higher pressure storage cluster was used to prepressurize the system. The contaminant levels dropped drastically during cryogenic pressurization (Scans 6 and 7). Although the low pressure storage clusters are filled initially with clean, cryogenic argon, when they are depleted by repeated use each tube apparently acquires its own level of residual contamination from back diffusion, depending on the circumstances of its exposure to the autoclave during the initial heat/pressurize portion of the HIP cycle.

The scans made after the HIP cycle (8, 9, and 10) ahow a significant decrease in contaminant levels as a result of dilution by the clean argon introduced to the system during direct cryogenic pressurization. The slight increase in contaminant levels in the last scan apparently resulted from back diffusion of air into the system during depressurization and venting of the process gas into the atmosphere.

In a final experiment, it was shown that the post HIP cooling rate, which can affect material properties and process time, is a function of both autoclave size and the construction of the thermal barrier system. This is illustrated in Figure 10.

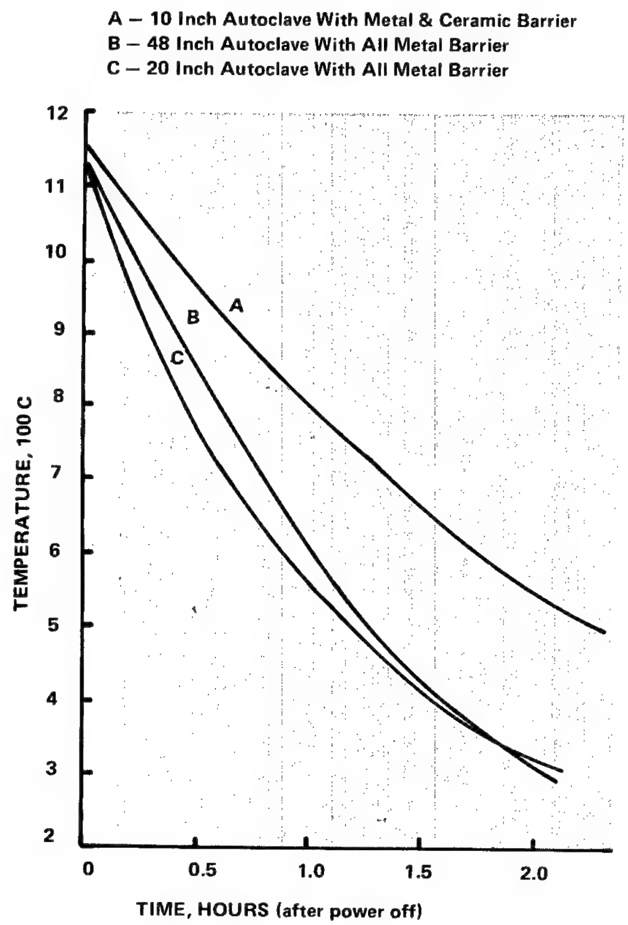
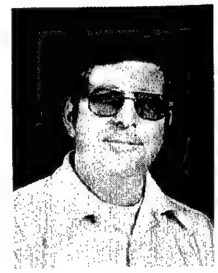


Figure 10



J. C. PFEIFFER is a Senior Process and Development Engineer with ICI Americas Incorporated and is responsible for the development, installation, and checkout of the black powder process control system at the Indiana Army Ammunition Plant. He currently is assigned as Proveout Manager for the new manufacturing facility. Mr. Pfeiffer is a graduate of Christian Brothers College with a B.S. in Electrical Engineering. He is a Registered Professional Engineer in both Kentucky and Indiana.

Automated System Adaptable Elsewhere

Computer Control For Black Powder Manufacture

Combining a process computer and programmable analog controllers, the U. S. Army Armament Command has built a completely automated, remotely controlled facility for the manufacture of black powder. The control techniques used can be easily applied to any process and are especially adaptable to material handling systems. In the case of black powder manufacture, the integrated system has achieved the design goals of process safety and reliability through a systems engineering approach. An important advantage from an initial cost viewpoint is that the system can be implemented in stages—installing the controllers first and adding the process computer at a convenient later date.

The new facility, which will be contractor operated, is presently in the proveout phase at the Indiana Army Ammunition Plant. Although black powder manufacture is an extremely old process, this new process marks the

Legend

A – Process Control Center
B – Area Control Point
C – Substation
D – Boiler Room
E – Maintenance Shop
F – Change House
G – Raw Materials Building
H – Process Building
I – Glaze Houses (4)
J – Screen House
K – Pack House
L – Conveyors

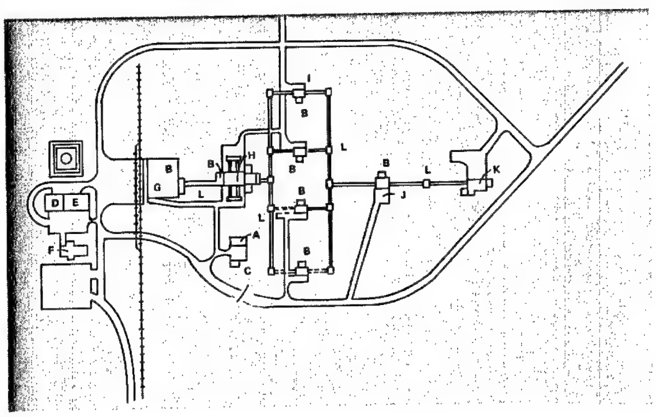


Figure 1

NOTE: This manufacturing technology project that was conducted by ICI Americas, Inc. was funded by the U.S. Army Armament Materiel Readiness Command under the overall direction of the U.S. Army Office of Manufacturing Technology, DARCOM. The ARRCOM Project Engineer is Mr. Gary McCloskey (812) 282-8961, Ext. 7403.

first time it has been instrumented and automated. In this new facility, only two of eight buildings involved in the process are occupied during production. Thus, the automated system will not only reduce costs and improve reliability, but—of greater importance—it will sharply reduce personnel exposure to hazardous operations. Black powder is easily ignited by static electricity, impact, and other conditions. Most accidents in the past have resulted from human error; such error is now eliminated and the isolation of personnel protects them from any accidents that might occur.

An Old Process

Black powder, which is more commonly known as gunpowder, has been produced for centuries. The Chinese first discovered that proper blending of sulfur, charcoal, and potassium nitrate produces an explosive material. Modern day explosives have replaced black powder for most applications, but it is still heavily used for the ignition of artillery charges.

Through the years, methods of manufacturing black powder have changed very little. Existing black powder plants use virtually no instrumentation and most processing is manually controlled. In the basic black powder manufacturing process, the sulfur, charcoal, and potassium nitrate are mixed in proper proportions, blended, reduced to proper particle size, moistened, and pressed into cakes of a specified density. The pressed cakes are then broken into granules, dried, and glazed with graphite. The finished product is classified by granule size and packed into 50 pound containers. Thus, black powder manufacturing is predominantly a materials handling process, including both batch and continuous operations.

Operations Isolated

In the Army's new facility, the various operations are conducted in eight separate buildings—a raw materials building, a process building, four glass houses, a screen house, and a pack house. These buildings are spread over a wide area to isolate operations and minimize concentrations of black powder. They are interconnected by conveyors, as shown in Figure 1. Only the raw materials building (where bagged materials are introduced into the process) and the pack house (where the finished product is packed into 50 pound containers) are occupied during production. Processing in all other buildings is remotely controlled at the process control center and supervised or monitored via closed circuit television.

Control System Design

The process control system for the automated facility was developed to meet requirements for

- Rapid shutdown
- Dynamic fail-safe action
- Total remote control
- Centralized control
- Semiautomatic backup
- Remote manual backup.

To form a total system concept, these requirements were integrated with basic design concepts for safety, reliability, accuracy, flexibility, optimum production, ease of operation, and ease of maintenance. In meeting these needs, the process control system was designed around seven area control points and one central control point. Each area control point focuses all control operations within that area on a central point. The area control points are in motor control center buildings that contain motor starters, power distribution equipment, and all control system interface equipment.

The central control point, or process control center, ties the area control points together and provides actual process control. From this center, operators monitor and control all operations. Signals and measurements to and from the process equipment are transferred from the area control points through an underground conduit system to the process control center.

The process control system includes three distinct subsystems:

- Process Controller or Computer
- Digital Control
- Analog Control.

Each subsystem can function separately or as an element of the overall system. Also, each subsystem is designed to check the other subsystems to insure proper operation. The **process controller** provides overall process supervision, monitoring, and control but does not have direct control over the process. Rather, it functions through the other two control systems.

The **digital control system** cannot issue commands by itself. Instead, it acts through either the operator or the process controller. This provides a double check system

whereby the process controller issues startup commands which are relayed to the digital control system. If the commands do not violate the digital control system's shutdown logic, the equipment will start up.

The **analog system** receives its setpoints and direct digital commands from the process controller. If the process controller fails to act on a measurement alarm, the analog control system sends a command to the digital control system to shut down the appropriate equipment.

Three Operational Modes

The process control system operates in one of three modes:

- Full Automatic or Process Control (PC)
- Semiautomatic or Auto
- Remote Manual or Manual.

There also is a local manual mode for maintenance.

Under the **PC Mode**, all three control systems function together. The process controller sends startup commands to the digital control system and monitors and sends set point and direct digital control signals to the analog control system. Using this mode, process parameters are optimized and all process data is recorded.

Under the **Auto Mode**, the process controller no longer plays an active part and can be shut down. The analog control system switches to its backup mode and performs all control functions through panel mounted controllers. The digital control system switches over to the Auto Mode and accepts commands from the operator. Also, various processing units can be controlled by their own control systems and panels. With this mode, the process will continue to operate but without optimization and logging of process data.

The **Manual Mode** is used for maintenance and system checkout and allows the operator to control various units manually from a remote location.

Plant Operation

In operation, the manufacturing process will be started on a Monday morning when the operator initiates the Prestartup Data Entry program from the teletypewriter. This is a question and answer program with the operator entering data on the type of production run for the week—class of black powder (grain size), formula, production rate, for example. Various system parameters are also initiated at this time. When all necessary data is entered, the operator initiates the Prestart program, which checks the status of all process buildings and utilities and starts up equipment such as wet scrubbers. When all checks are made and all conditions are satisfactory, the various startup programs are automatically initiated.

Startup begins with an operator in the raw material building loading the hopper. When the hoppers are filled to a minimum level, discharge begins and raw materials are fed to the process building. The process startup continues until all systems are started. Production continues under the full automatic control of the process computer and the digital and analog systems.

At any time during a production run, the operator can enter preshutdown and shutdown times. At these preset times, the process controller automatically starts the preshutdown and shutdown sequences.

Startup, operation, and shutdown are not the only functions of the process controller. Product quality is checked continuously and equipment such as the weighing scales are corrected to ensure continuous uniformity in the product. The various measurements are checked extensively to determine their reliability. Also, material balance is continuously monitored, with reports available upon demand. This is just one of several generated by the process controller. All process parameters are stored for easy access in tabular form and modification by the process engineer as necessary.

Although the system is controlled by the process computer, the operator or process engineer can interrogate all analog and digital inputs and outputs via the operator's console and then perform functions such as changing an analog controller's tuning parameters or starting a motor. If the process computer appears to malfunction, the operator can assume control by switching to the Auto Mode. In this mode, the operator will use the panel mounted analog controllers, the manual interface panels, and the graphic display, along with various equipment control panels located on the process control console.

Safety Stresses

Safety and reliability are prime concerns in controlling a hazardous process. To ensure safety in the new system,

backup is provided by use of two computers in series—one complex (the process computer) and one simple (the programmable controllers). The series concept has several major advantages over the alternative parallel computer concept.

First is the rapid response time—the time to recognize and act upon an abnormal situation. Most large process computers require a long time to recognize an abnormal condition. In the black powder manufacturing process, a process computer (parallel concept) could take a second or more—under some conditions, several seconds or even minutes—to recognize an abnormal condition and even longer to initiate corrective action. This is because of lengthy programs involved. The programmable controller (series concept) is guaranteed to recognize an abnormal condition in one scan period and take full action in the next scan period—a total time of 500 milliseconds maximum. Due to the rapid burning rate of black powder, milliseconds may make the difference between a minor problem and a major disaster.

The second advantage is that with the two computers connected in series both computers must fail or make the same mistake for the process to be affected. In a parallel system made up of two similar computers, both computers can make the same errors since both programs are basically the same. Also, a parallel system does not normally provide a complete double check of operations but merely process monitoring by the supervisory computer.

The third advantage is that there are two completely different types of programs—one far simpler than the other. The interlocking and safety shutdown logic is in the programmable controllers, with their very simple programming system. It is far easier to make sure that the programmable controllers contain the correct logic than it is to check out the large process computer programs. The noncritical sequence steps are in the complex computer, while the critical shutdown logic is in the simpler computer or programmable controller. A parallel system has all programming and logic in two large, very complex computers. The series connection thus reduces the possibility of computer generated accidents due to software or hardware failures.

Operator generated errors are reduced by the elimination of manual operations while the system is in the PC Mode. During the Auto or Manual Mode, all operations are via the manual interface panels and must agree with the programmable controllers' logic, which, as mentioned above, is a relatively simple program to check out. The programmable controllers themselves cannot initiate commands but can only process commands sent by the process computer or operator.

Cost Kept Low

Several key features help reduce maintenance costs for the process control system. First is the centralization of controls. All control signals within a processing area are routed directly to one central control point where they are gathered and either multiplexed or directly wired to the process control center rather than routed to various control cabinets and panels throughout the processing area. This reduces the number of failure locations to three--the process control center, the area control point or the device itself. The failure location can easily be determined by use of the manual interface panels.

Next, virtually all relay cabinets have been replaced by two programmable controllers that provide high reliability through solid state electronics. Troubleshooting has been simplified by the manual interface panels, which allow the operator to directly interrogate devices. A special key switch is provided to allow the operator to bypass all internal interlocking logic within the programmable controllers. If a motor won't start, the operator can bypass all interlocks and try to start the motor. Thus, the operator can separate hardware and software problems. Virtually all problems can be resolved from the process control center. Indicators on all digital input and output modules are further aids in troubleshooting.

Modifications to the system were simplified by eliminating rewiring of large relay cabinets. A motor can be added by simply wiring the motor itself, adding a local start/stop button, and adding a few wires to the digital input/output modules. All other changes are in the software.

The process control console is also designed to facilitate changes. It uses 19 inch relay racks instead of the standard solid metal front panels. A panel section is easily removed, modified, and replaced.

Efforts were also made to keep installation costs down. With the process spread over a wide area, these costs were reduced by multiplexing as many signals as possible. The type of programmable controller used allows multiplexing of the majority of the digital signals. All wiring was directly routed to a central point in a processing area, simplifying conduit systems and reducing the amount of conduit required. The extensive use of software rather than direct wired controls further reduces the number of control wires and conduit.

Need for High Density Circuits Met

Semi-Additive Fabrication of Printed Wiring Boards

Printed wiring boards now can be fabricated by a semi-additive process developed at Hughes Aircraft which has proven effective in overcoming shortages of conventional systems and meeting demands of modern electronic systems. Printed wiring boards fabricated from four different epoxy-glass laminate types meet the requirements of military specifications and make practical the fabrication of high density circuits; they also can be produced at reduced labor costs. Hughes' developmental effort was sponsored by the U.S. Army Missile Research and Development Command.

Achieving its advantages through use of different materials and process refinements, the new process incorporates normal subtractive printed wiring board fabrication techniques to a large extent. However, it is also adaptable to production of all copper circuits through use of solder dip/air leveling equipment. In this case, the solder coating replaces the conventional tin-lead plate. The process also lends itself to use of a permanent solder mask.

Using the modified process to produce all copper circuitry, labor costs can be reduced by as much as 9 percent. Although this savings is offset to some degree by higher material costs for all but one of the laminates, overall cost reductions are still possible. However, the primary benefit remains the ability to fabricate high density boards to specification through a techmique that can be easily implemented to standard subtractive production lines with minimal conversion costs. Other benefits include greater reliability and better environmental pollution control.

Applicability of the process was verified in pilot line production at Hughes. Both medium and high density printed wiring boards were produced to meet the requirements of MIL-P-55110 for printed wiring boards. The pilot

ROBERT L. BROWN is a General Engineer at the U. S. Army Missile Command in Huntsville, Alabama. His current projects involve creative direction of contractor engineers on projects such as the fully additive manufacture of printed wiring boards (Hughes), ultraviolet curing of conformal coatings for PC boards (Hughes), product cleanliness techniques for PC boards (Martin-Marietta), laser scan testing of PC boards (Chrysler), rigidflex assemblies (McDonnell-Douglas), and insertion of nonaxial lead devices in locaserts (Martin-Marietta), a recent approved success. A Registered Professional Engineer in Alabama and holder of a B.S. in Metallurgy (1958) from Alabama University, Mr. Brown holds six patents and is author of fifteen technical briefs which NASA rates as equivalencies to patents. He was the first recipient of the NASA "Noteworthy Contribution" award in 1970 for his many contributions to their technical utilization program, and patented several inventions that were used in production. While employed by Chicago Bridge and Iron in 1948 he invented an early television X-ray imaging system, which was the first such system to reach broadcast resolution and was the basis of an X-ray television system built by Zenith Corp. and delivered to Marshall Space Flight Center in 1972. This system was used at Vanderbilt University as the best available nuclear medical imaging system and is still in use there as a television X-ray system. His most recent development of an X-ray imaging system is characterized by revolutionary increases in resolution and performance through use of fiber optic technology, in which 80-100% of the radiation is captured in the image and resolution is more than 20 lines per inch, with increases easily possible through use of finer fibers. Also while at Chicago Bridge and Iron he patented a method for brazing claddings on dissimilar metals which was widely used commercially for many years. A member of the International Society of Microelectronics, Mr. Brown worked as an aeronautical engineer during World War II at Birmingham and also worked as an engineer with the Birmingham Fabrication Company.

NOTE: This manufacturing technology that was conducted by Hughes Aircraft was funded by the U.S. Army Missile Command under the overall direction of the U.S. Army Office of Manufacturing Technology, DARCOM. The MICOM Project Engineer is Mr. Bob Brown (205) 876-5742.

line utilized inplace equipment used for standard production. However, an automated production line concept was taken through the design stage.

Present Methods Fall Short

Traditional methods for fabricating printed wiring boards are not adequate to meet the demands of today's lightweight, compact electronic systems for higher density circuits. Conventional technology is based on a subtractive process—a resist image is applied to a metal clad dielectric laminate and the excess metal is etched away. Development of reliable photoresist systems that negate the effects of plating chemicals has led to the use of pattern plating techniques to modify and refine the basic process. Applying these techniques, the printed wiring boards fabricator can limit copper electroplate and tin-lead deposits to the through holes and circuitry patterns. Once plating is finished, the resist is removed and the unwanted copper foil is etched away. With these refinements, reliable, high density printed wiring boards with 0.010 inch conductor lines and spaces are produced in quantity.

However, for high density electrical packages, materials and processes that can produce 0.005 inch lines and spaces are required. The Hughes' program was directed toward use of semi-additive and ultrathin, copper clad techniques to provide this capability. It included two phases—an 18 month developmental effort and a 12 month effort to establish a pilot production line.

Four Laminate Types

Four types of epoxy-glass laminates tested during the developmental effort met printed wiring board requirements. These materials fall in two major categories—ultrathin copper clad laminates and unclad additive type laminates. These material types are illustrated in Figure 1.

The ultrathin laminates include both peelable and etchable materials. Both types have an ultrathin copper foil (one-eighth ounce/square foot or 5 micrometer copper thickness) overlaid with a protective carrier metal. On the **peelable laminate**, a 1-1/2 to 2 ounce/square foot copper carrier foil is attached by a weak bond. This foil provides a protective layer through the processing operations. After the through holes are drilled (prior to electroless copper plating), the foil is peeled off. This leaves a clear copper cladding surface that can be processed immediately without deburring or cleaning. The **etchable laminate** has a thin aluminum protective layer that serves the same purpose. It is chemically removed after drilling.

There are also two types of unclad laminates—sacrificial foil and adhesive coated. The **sacrificial foil** type is an epoxy-glass laminate covered with anodized aluminum foil whose anodized surface is bonded directly to the epoxy resin surface. When this foil is etched away after drilling, a replica of the anodized surface finish remains in the epoxy. The highly textured surface provides bonding sites for mechanical attachment of the electrolessly deposited copper.

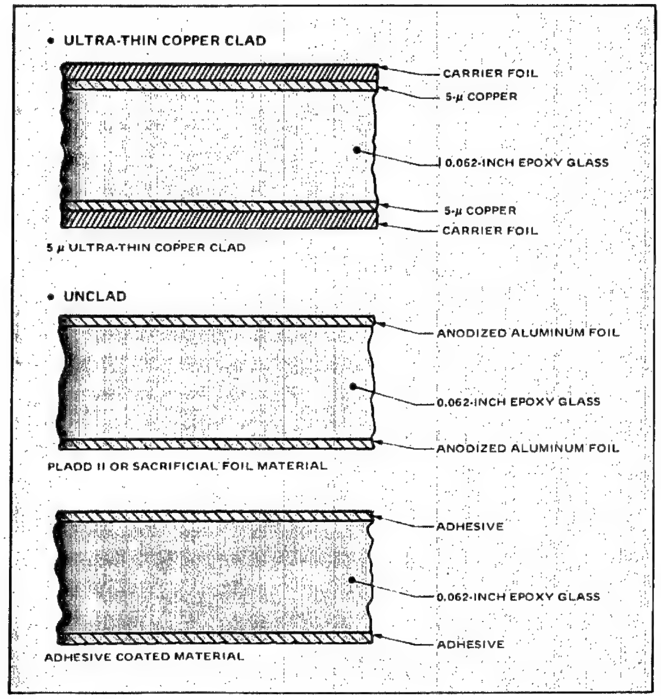


Figure 1

The **adhesive coated** epoxy-glass laminate is coated on both sides with a proprietary adhesive. After drilling, the adhesive is conditioned using chromic sulfuric acid followed by neutralization in sodium metabisulfide solution. Initially, printed wiring boards fabricated from this laminate did not meet insulation resistance requirements following humidity exposure. This problem was overcome by dissolving and removing the adhesive layer between the circuitry patterns with a liquid fluorocarbon/methylene chloride solvent. Subsequent tests indicated that the solvent treatment did not affect peel strength, an important printed wiring board criterion.

Process Development

Test panels using a Hughes modified IPC test pattern (Figure 2) were fabricated from each of the four material types. Steps in both the ultrathin process and the semi-additive process using unclad laminates are shown in Figure 3. Steps for the conventional subtractive process are also given, indicating that most steps are common to the three processes. These panels were plated in a low rate (30 microinch/30 minute) electroless copper system at room temperature followed by a pyrophosphate copper

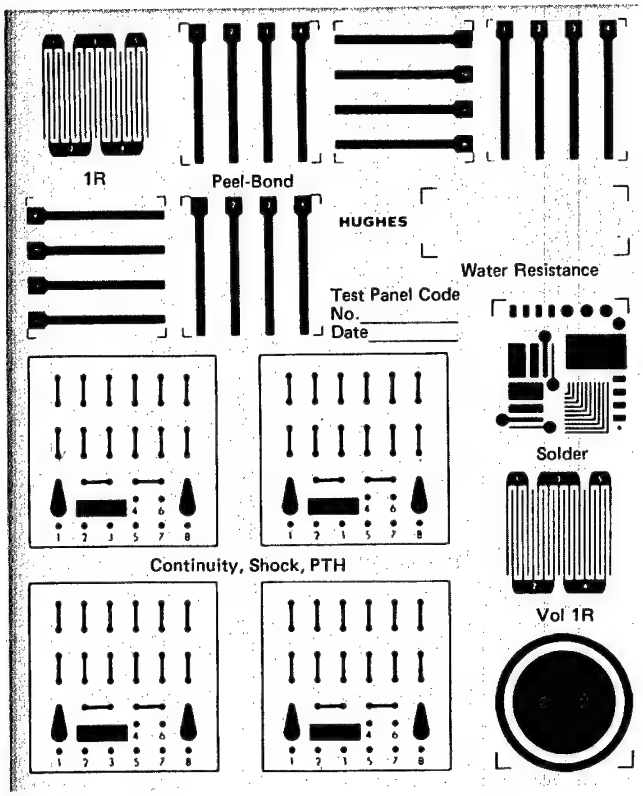


Figure 2

plating bath. All panels were plated with a minimum of 0.001 inch of copper in accordance with MIL-P-55110 requirements. Results of visual, plating adhesion, peel strength, and warp and twist test indicated that all four materials were qualified for further process evaluation. Extended peel strength tests were conducted to ensure against latent failures, and in all cases strengths exceeded MIL-P-13949 requirements as shown in Table 1.

Material Information		Determined Peel Strength, lbs/in. of Width			
Vendor	Laminate Description	At Room Temp	After Solder Float	At 125°C Temperature	After Temperature Cycling
I	Ultra-thin copper clad, peelable carrier	7.9	8.2	6.4 −0.5 ±0.3	8.1 −0.2 +0.2
I	Ultra-thin copper clad, etchable carrier	8.9	10.7	8.1 −1.0 +0.5	8.7 −0.5 +0.4
C	Unclad laminate--Adhesive coated	18.1	20.6	7.5 −2.2 +3.1	17.2 −0.1 +0.1
A	Unclad laminate–Sacrificial foil	10.0	8.7	6.1 −0.4 +0.6	10.7 −1.6 +1.1
MIL-P-13949 Requirements (Minimum requirements for 1 oz/ft^2 copper)		No Requirement	8.0 (6.0)*	5.0 (5.0)	8.0 (6.0)

All average values based on at least 3 test results from 4 individual test panels. All tests performed from plated copper = 1 oz/ft^2.

Table 1

*MIL-P-55617 requirements in parentheses.

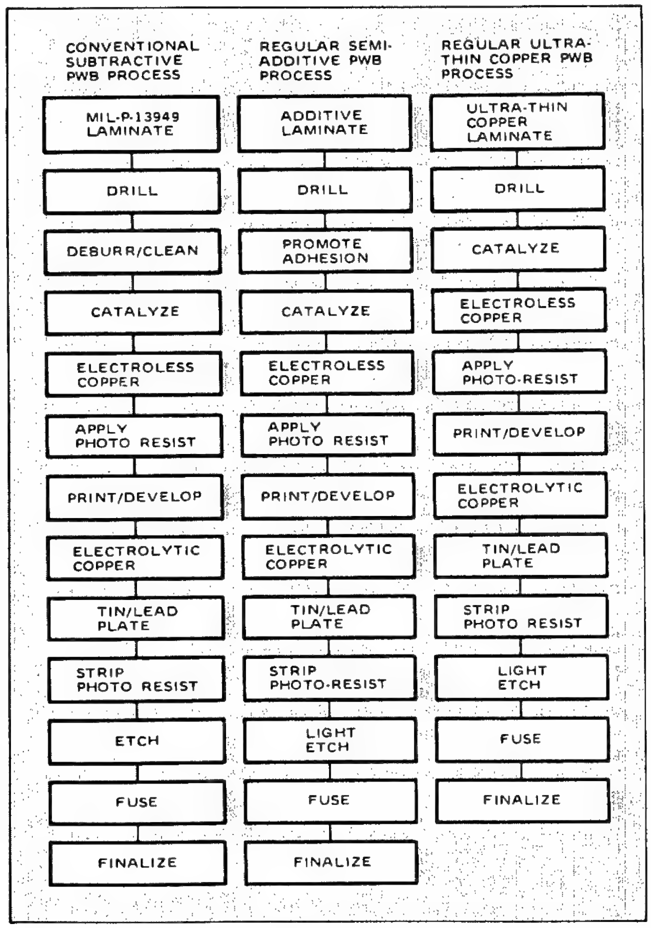


Figure 3

Peel Strength Important

In optimizing the process, peel strength tests provided an important criterion. Surfaces of the four materials were examined by a scanning electron microscope following various surface preparations to compare surface finish with peel strength. Effects of the electroless copper catalyst system on peel strength were also evaluated. As a result, a 50 angstrom acid catalyst and a high rate (70-100 microinches/minute) electroless copper system that yields a coarse grained deposit were selected for evaluation of additional test panels. The high deposition rate was required to eliminate electrolytic copper panel plating. With this system, peel strength of the deposited copper was good for both unclad laminate types.

Standard tin-lead plating and fusing techniques were employed to fabricate these panels. The processes were designed to provide 70 microinches of electroless copper, 0.01 inch of electrolytic copper in the plated through holes, and 0.0003 inch of tin-lead. Panels from all four materials met the requirements of MIL-P-55640.

"Resin bleed through" and drill burrs at the through holes were potential problems with the ultrathin copper clad laminates but did not develop. Burrs were prevented by sandwiching the printed wiring boards between an aluminum entry foil and an aluminum backup board for drilling and carefully monitoring drill feeds and speeds.

Process Modification Drops Cost

Preliminary cost analyses indicated that all of the materials except the sacrificial foil laminate were more expensive than standard MIL-P-13949, 1 ounce/square foot material 0.062 inch thick. The ultrathin copper clad materials cost 14 to 16 percent more and the adhesive coated laminates 9 percent more. The sacrificial foil laminates cost about 7 percent less. However, significant labor savings—about 9 percent for ultrathin material and about 7 percent for sacrificial foil—can be realized using a modified process to produce all copper circuits. Appreciable savings may also be realized in increased yields (3 to 5 percent) and reduced need for etchant material (one eighth the cost of that needed for 1 oz copper).

The modified process for all copper boards deposits a heavier layer of copper (0.002 inch) onto the board in the circuit pattern area and the through holes. In this modified process, the boards are not tin-lead plated, but are flash etched to remove the ultrathin copper foil and 70 to 100 microinches of electroless copper in the unwanted areas. The flash etching also removes copper in the pattern area, but the extra initial thickness ensures that the minimum requirement of 0.001 inch is met. The method lends itself to the use of solder coater/air loading equipment for application of solder to the circuitry and the plated through holes resulting in a cost effective method of producing solder coated printed wiring boards and an overall labor savings.

Pilot Production Process Set

Figure 4 compares the steps in the regular and the modified ultrathin copper clad processes. The regular process utilizes standard printed wiring board fabrication techniques of drilling, hole plating, imaging, pattern plating of copper and tin-lead, etching, and fusing. The modified process to produce all copper printed wiring boards eliminates tin-lead plating and fusing from the sequence. Printed wiring boards were also fabricated using this modified process with a permanent solder mask. Steps in this variation are also shown in Figure 4. Printed wiring boards fabricated by all three processes met test requirements.

Because the regular process most closely paralleled production processes at Hughes-Fullerton, it was chosen for initial pilot production line development. To firmly establish parameters to ensure uniformity and conform-

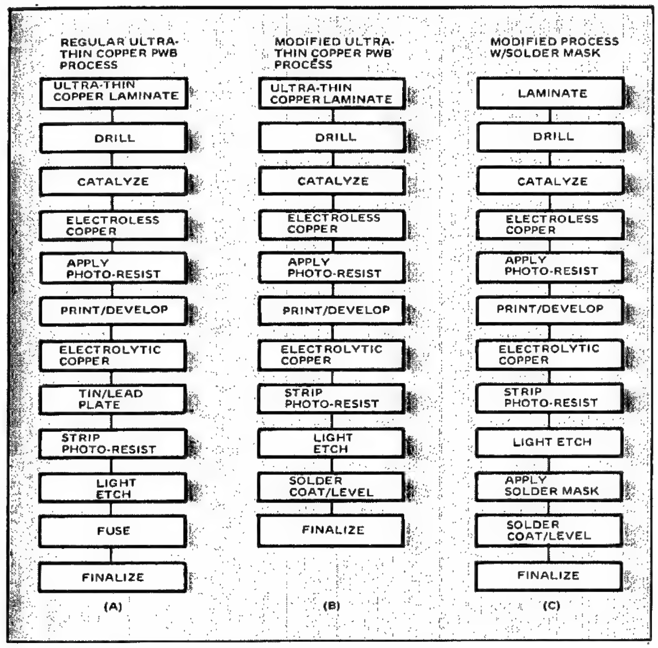


Figure 4

ance to MIL-P-55110, the basic process was further refined and modified by fabrication of five tests sets of two printed wiring boards each. Thus, a production process capable of routinely producing acceptable printed wiring boards was established.

Production Process Verified

Based on this process development, a pilot production line, utilizing an unbalanced concept with processing tanks and equipment in different locations, was layed out for the ultrathin copper clad material. Use of the unbalanced concept eliminated the expense of establishing a new production area. A flow diagram of the process steps is shown in Figure 5.

Precise controls were provided at all steps from generation of engineering data and plans through application of materials and chemical solutions in fabrication to final cleaning and packaging.

The production line was qualified by routine testing of printed wiring boards fabricated from peelable materials. After preliminary tests indicated acceptable plated through holes were being produced, ten production type printed wiring boards were fabricated and tested in accordance with MIL-P-55110. The results established conformance to requirements, then production quantities were run over a 3 month period. The regular ultrathin process was used to produce approximately 450 medium and high density boards. About 150 additional medium density boards were produced using the modified process

Another 40 boards were produced using the permanent solder mask. Printed wiring boards were tested at random during these runs. All boards tested met printed wiring board requirements.

Specifications for an automated production line using conveyors, numerical control tape, and a computer were prepared. These specifications included a four spindle NC drilling machine and an automated sensitize and electroless copper plating line. Only the application of the photoresist to the laminate materials remains as an operator controlled task in this design.

Hughes has prepared a 15 minute 16 mm motion picture depicting the complete manufacturing process and highlighting those steps that are unique to the semi-additive or ultrathin copper processes. Hughes has recommended that military specifications be updated to permit the use of one eighth ounce/square foot or 5 micrometer copper clad laminates in printed wiring board production.

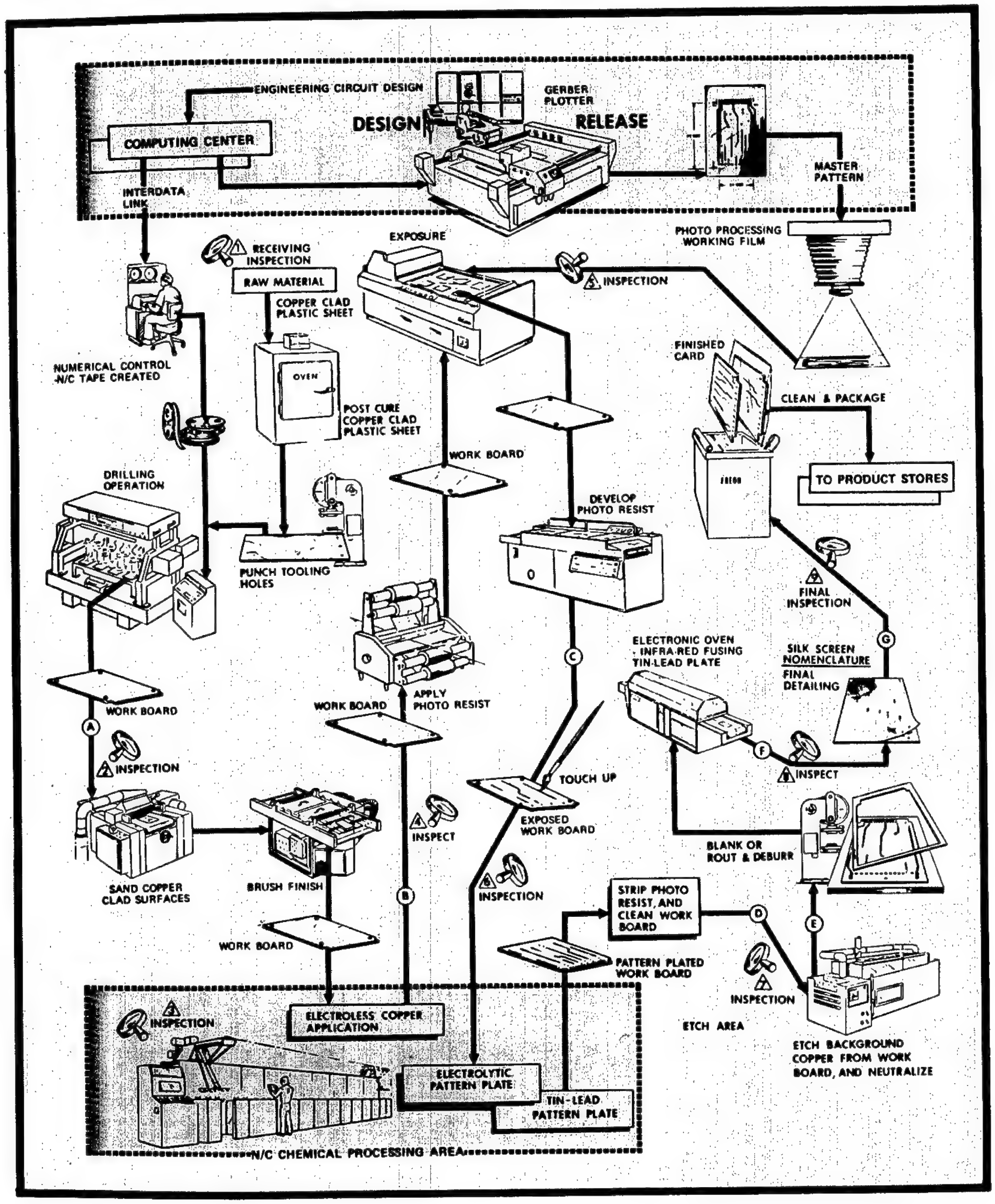


Figure 5

Labor Reduced Over 90%

Mechanical Benching of Artillery Tubes

PHILIP CASEY joined Watervliet Arsenal's Machine and Methods Technology group in 1957. He has been Project Leader on many special equipment applications related to the production of cannon barrels and since 1975 has supervised the Machine Development Unit at Watervliet. Consulted with and contributed to weapon systems' producibility of design. Mr. Casey is a member of the DARCOM Metal Removal Working Group and a past member of the DoD Chip Removal Conference. He currently serves on the DoD Manufacturing Technology Advisory Group's Machine Tool Task Force.

Development of a motor driven tool for benching operations inside 152 mm artillery tubes has proven to be a real labor saver at Watervliet Arsenal. Benching is needed to remove burrs at intersection points between grooves in the weapon bores. Hand benching, largely a trial and error process requires more than 40 hours per tube. Watervliet's motor driven tool, which is attached to a borescope that allows the operator to view his work, has cut that time to just 3.05 hours per tube. It was developed during an MM&T project in the Benet Weapons Laboratory.

Benching operations are performed on manufactured parts to remove sharp corners and burrs. Generally, the benching is done with hand held tools—files, grinders, etc. It becomes a difficult process in long weapons barrels because of problems in controlling the tool and viewing the actual operation. Mechanizing the process eases these problems.

Special Barrels Require Benching

Weapon tubes will not necessarily require benching, but the 152 mm M162 and M81 gun systems are special cases. These weapons are designed to fire both conventional spin stabilized rounds and the nonrotating Shille-

NOTE: This manufacturing technology project that was conducted by the Benet Weapons Lab, Watervliet Arsenal, was funded by the U.S. Army Armament Research and Development Command under the overall direction of the U.S. Army Office of Manufacturing Technology, DARCOM. The ARRADCOM Project Engineer is Mr. Gary Conlon (518) 266-5737.

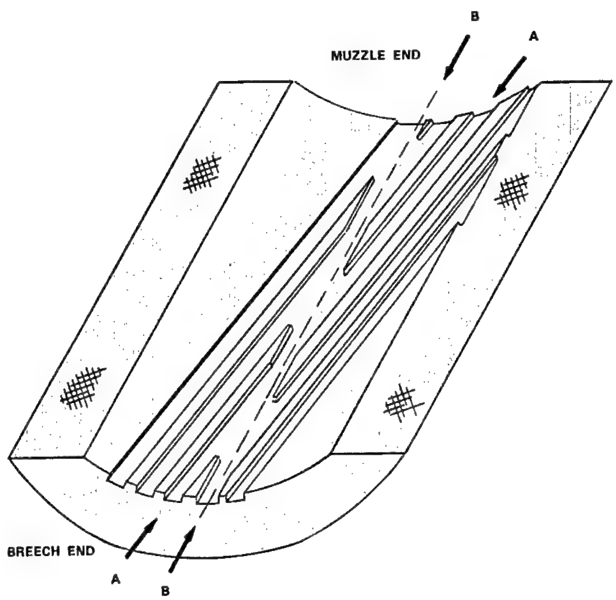


Figure 1

lagh guided missile. Standard rifling grooves are used to stabilize conventional rounds, and a straight groove cut down the length of the bore orients the Shillelagh missile prior to guide control. This bore configuration provides a flexible weapon, but it also creates a manufacturing problem. Both grooves are machineable using well controlled processes and, therefore, readily producible. However, at the points where the grooves cross, weak burrs are produced. In tests, these burrs fold into either the missile or rifling groove and interfere with firing. Because no conventional machining process is available for the job, the burrs must be removed by hand benching.

The bore configuration is shown in Figure 1. The single missile guide slot (Slot B) is parallel to the bore centerline. There are forty-eight rifling grooves, represented by Slot A, lying in a spiral pattern. Many of these grooves intersect the straight missile guide slot to form burrs. As seen in the figure, the first intersecting point is on the left of the missile slot, pointing toward the muzzle end. The second point is on the right side of the missile slot, pointing toward the breech end. Each rifling groove that intersects the guide slot produces this pattern. In a 100 inch long tube—the length of current production tubes—this pattern occurs eighteen times, producing a total of thirty-six burrs that require benching.

Hand Operation Inadequate

Since the bore diameter is only six inches, the normal approach to hand benching is most difficult. There is no way that an operator can control a hand tool four feet away within such a confined space to consistently produce an accurate configuration.

During the experimental phase of component development, the burrs were removed by taping files onto long sticks, inserting them into the bore, and attempting to file in the area of each intersection. After removing the tool, the operator would visually check the work using a borescope. If the burr still remained, the operator would try again. Repeated for each intersecting point, the entire operation took better than 40 hours—in some cases more than 50 hours. Furthermore, precise dimensional control was not possible. It then was concluded that a manufacturing technology program was needed to improve benching accuracy and reduce the cost.

Mechanical Design Solves Problems

To overcome the problems of visual access and tool control, a workhead was designed to be mounted on the end of a borescope. The resulting system is shown in Figure 2. The borescope tube supports tool control cables, electrical power lines for illumination, and air lines for position lock and motor drive. In the figure, Item 1 is the workhead mounted on the borescope tube (Item 2). Item 3 is the operator control area. A foot operated valve (not pictured), which controls shop air line pressure, is located at this site as are the push-pull cables for tool location, which are manually operated. The borescope eyepiece (Item 4) is also conveniently located in this operator control area.

The benching device is designed for use from either end of the tube, so the maximum depth only has to be half the bore length. However, because of the effectiveness of the unit, the 152 mm tubes are benched through their entire length from one end.

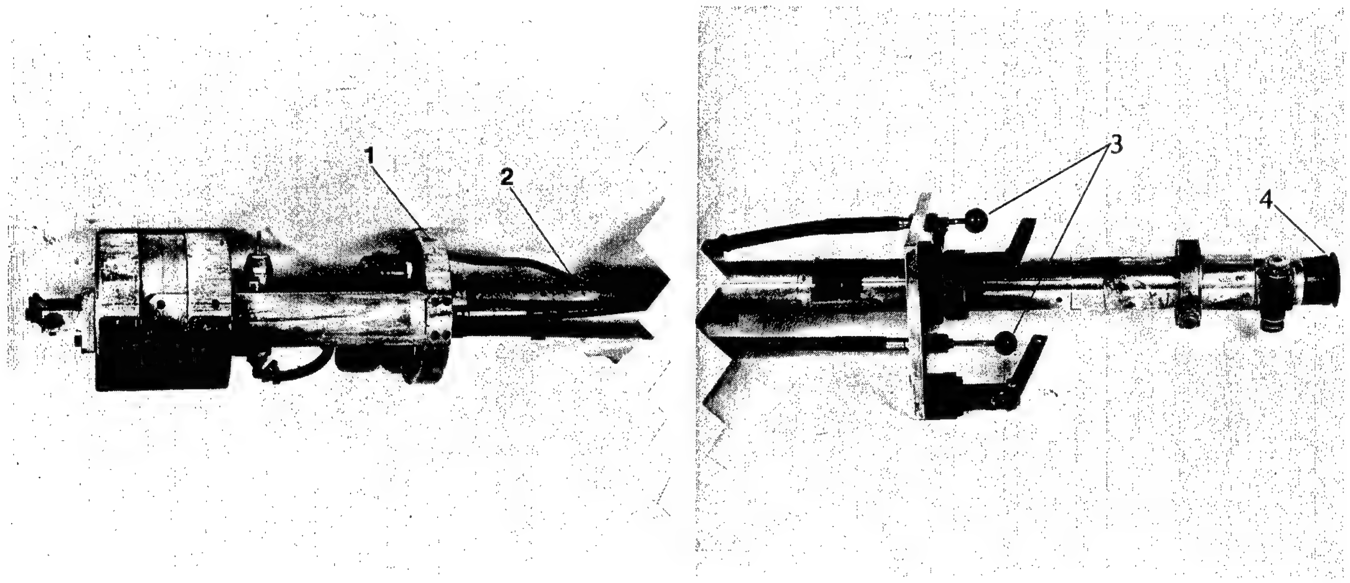


Figure 2

Accessibility Not Critical

Light bulbs (Item 5) are provided on the tooling to illuminate the work area. The operator uses the borescope optical system and viewing mirror (Item 6) to properly position the tool and to monitor the operation.

This tooling development has demonstrated that both significant cost savings and quality improvements can be realized by replacing hand benching operations with controlled tool motion regardless of accessibility problems.

Benching Tool Details

Figure 3 is a closeup of the workhead for this innovative tool. The size of the air motor (Item 1) was dictated by the bore diameter (6 inches maximum). A 75,000 rpm motor was selected. The motor is mounted so that the colleted carbide burring head (Item 2) extends out to the major bore diameter (groove depth). The motor mount provides a radial sweep about the bore centerline. As the tool rotates in this arc after being properly located along the bore, the burring head removes metal down to the bottom of the groove. Since the point to be machined is approximately 9/16 inch long and the burr diameter is only 1/8 inch, a longitudinal feed is also provided.

The operator controls both longitudinal and radial motion through the two push-pull cables. Longitudinal motion is obtained through a lever on the end of the workhead (Item 3) that actuates one cable to move the tool holder spindle. The other cable is affixed to a helical gear that, upon longitudinal motion, causes the mating fixed position gear to rotate (Item 4). These two motions provide the complete range needed to properly locate the tool at each intersecting point. A plunger in the workhead locks the tool in position after it is properly located. This lock and the air motor are activated by the foot pedal. When a burr is satisfactorily removed, the entire unit is moved to the next intersecting point and the process is repeated.

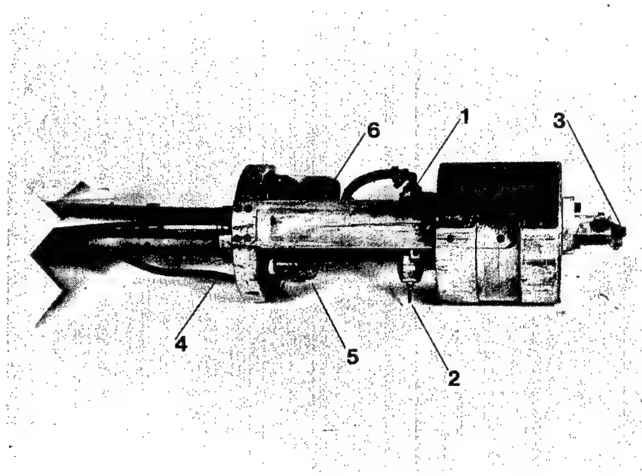


Figure 3

New Technique Saves Time, Improves Accuracy

Cannon Boring Automated at Watervliet

Through a series of MM&T programs, engineers at Watervliet Arsenal have developed an improved boring head for gun tube manufacture. This tool, with hydrostatic bearings and automated electronic guidance, has overcome several drawbacks of the earlier system. Used on various gun tubes with internal diameters of 4 to 8 inches, it reduces boring and tooling time (by nearly 50 hours on one tube) and improves boring accuracy.

Significant Breakthrough

Termed a real breakthrough by its designers, the new boring system has replaced the old "packed reamer" boring tool that had been used for more than 50 years. The old tool utilized reamers that depended on an interference fit in the finished bore and that had to be serviced after each operation. Actually, in many cases they could only bore half the tube length before servicing was required. Futhermore, the tool had to be operated at less than optimum feed and speed to avoid excess tool wear and bearing overheating. Successive improvements have resulted in the present hydrostatic bearing boring head shown in Figure 1. This head holds the cutting tools and is electronically guided to ensure bore accuracy.

Automatic Pilot Guide

The guidance system (seen in Figure 2) is much like the automatic pilot on a ship or plane—as a deviation from the planned course or heading is detected, a correction is made to "get back on course".

In the case of the boring head, the planned course is the axis of the rotating gun tube. When the head does not follow this axis exactly, it is said to "run out". An electronic detection device (accelerometer) senses any runout and signals the control console (shown in Figure 3) that a correction must be made. This message is relayed to activate a hydraulic servocontrol that moves the cutting tool at the proper rotational arc to correct the deviation. All of this is nearly instantaneous so that the corrective movement is accomplished while the tool advances only 0.0002 to 0.0003 inch. The surface variation that results from the deviation is imperceptible. Once the head is back on course, properly centered in the bore, the signal shuts off until further deviation is detected.

NOTE: This manufacturing technology project that was conducted by the Benet Weapons Lab, Watervliet Arsenal, was funded by the U.S. Army Armament Materiel Readiness Command under the overall direction of the U.S. Army Office of Manufacturing Technology, DARCOM. The ARRCOM Project Officer is Mr. W. A. Wondisford (518) 266-5590.

ROBERT H. CIPPERLY is a technical specialist in the Engineering Support Branch of the Benet Weapons Laboratory phases of cannon production. He has been an MM&T project leader and currently is responsible for progress reporting on numerous MM&T projects. He has served on various weapon teams and was a member of the evaluation committee for multiyear buy of the 155 mm M199 system. Mr. Cipperly is an altermate member of the DARCOM Metal Removal Working Group and was a delegate to the DoD/Industry Metal Chip Removal Conference. A graduate of the Watervliet Arsenal Apprentice Machinist program, Mr. Cipperly also holds an Associate Degree in Mechanical Technology from Hudson Valley Community College of Troy, N.Y.

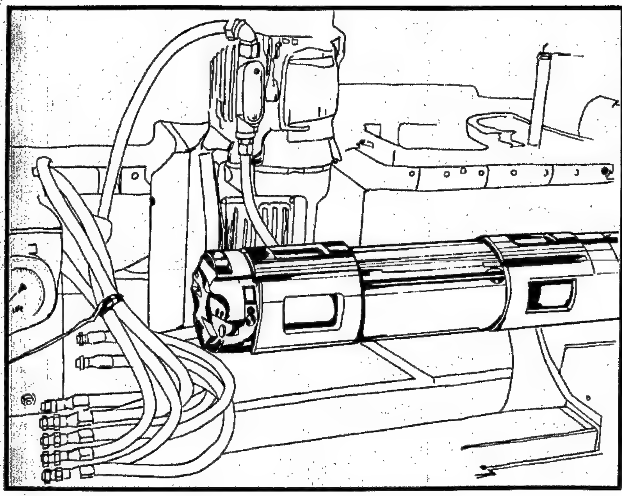


Figure 1

Sensors Provide Monitoring

Tube boring is a blind operation—the operator cannot watch the cutting taking place. Therefore, a means of monitoring certain aspects of the operation are built into the guidance system. The operator's console includes four readouts and a recorder (see Figure 2), which are used to monitor and record bore diameter, offset, runout, and bearing pressure. The latest boring head uses inductive sensors (proximity probes) that read these parameters through the bearing oil film without touching the bore. Limits for each parameter are set at the control console. When any readout exceeds the set limits, the boring feed automatically shuts off.

Bore diameter is monitored by two diametrically opposed inductive sensors mounted vertically on the boring head just behind the vertical cutting plane of the tools. When the boring head is completely within the tube, the limits on the readout are set at ±0.003 inch.

Automatic Shutdown Via Monitor

Offset describes the location of the boring head with respect to the bore in which it is riding. Again, two diametrically opposed inductive sensors measure offset. In this case, they are mounted horizontally on the head directly behind the cutting tools. Limits on the offset readout are set at 0.005 inch. Normally, the offset will vary only 0.00075 inch, which represents the correction taking place.

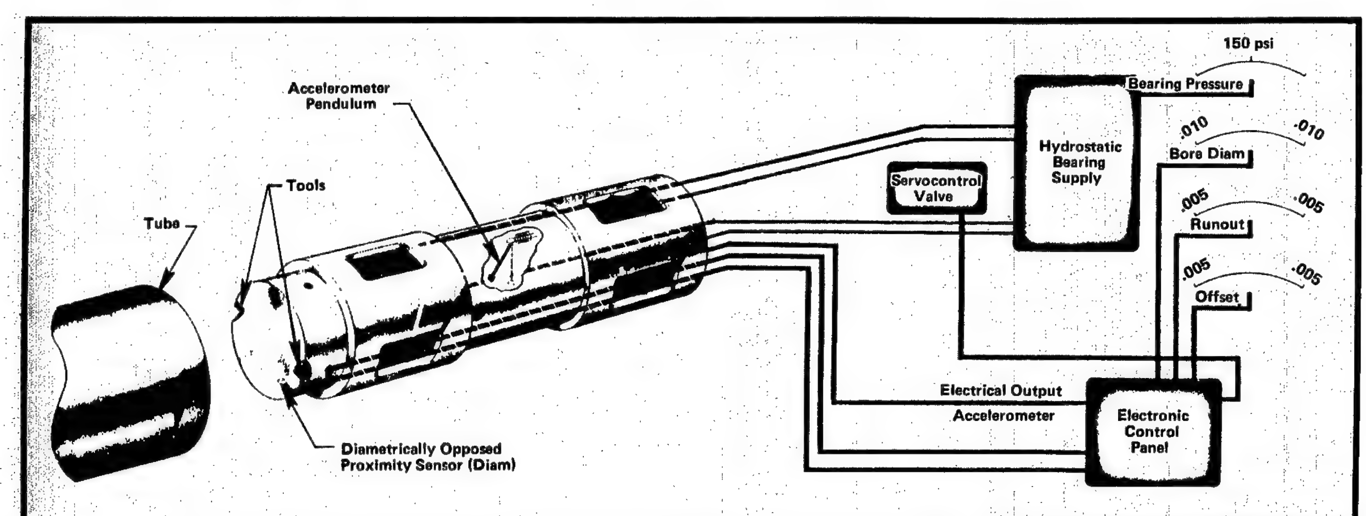


Figure 2

US Army
ManTech Journal

Productivity Growth In The 80's

THE DEPUTY SECRETARY OF DEFENSE

WASHINGTON, D.C. 20301

May 30, 1980

MEMORANDUM FOR THE SECRETARIES OF THE MILITARY DEPARTMENTS

SUBJECT: Manufacturing Technology Program

Each of you is aware of the critical production problems we are facing with acquisition and life cycle costs, long production lead times, and shortages of strategic materials. While we have addressed these problems from every conceivable aspect, many remain today. Therefore, we must make a renewed attack on these problems with sustained, new initiatives.

Use of technology to reduce manufacturing costs and to help in the resolution of our other production base problems is a major Research, Development and Acquisition Program initiative for the 1980's. The DoD Manufacturing Technology Program is spearheading this thrust; the attached Statement of Principles outlines its foundation. Its basic objective is to improve the productivity and responsiveness of the defense industrial base by sharing with industry the risks and costs of establishing and applying new and improved manufacturing technologies.

Improved productivity not only exerts tremendous positive leverage on defense systems acquisition and life cycle costs but also is a basic element of economic growth. It is intimately related to inflation, unemployment and the competitiveness of U.S. products in both domestic and world markets. There are numerous examples where Manufacturing Technology Program spinoffs into the overall economy have significantly increased productivity. A classic example is the development of numerically controlled machine tools. Their application in the defense and private sectors has saved billions of dollars in metal removal costs.

I am convinced the aggressive implementation of the initiatives outlined in the Statement of Principles will significantly aid in the reduction of acquisition and life cycle costs. I solicit your personal assistance and involvement in carrying out this program.

Within 120 days I would like for you to arrange for a briefing for the Under Secretary of Defense for Research and Engineering who will then summarize for me the steps you have taken to pursue the individual elements of the Principles. In addition, I would appreciate learning about any specific major initiatives you have undertaken within this program and any additional ideas you may have for increasing manufacturing productivity and reducing manufacturing costs.

W. Graham Claytor, Jr.

W. Graham Claytor, Jr.

Attachment

DR. ARDEN L. BEMENT, JR., is Deputy Under Secretary of Defense for Research and Engineering (Research and Advanced Technology). He is responsible for overall management of the science and technology programs of the Department of Defense and for related activities such as manufacturing technology and monitorship of the DoD in-house laboratories and Federal Contract Research Centers. From 1976 through 1979, Dr. Bement was Director of Materials Sciences, Defense Advanced Research Projects Agency, responsible for research in structural, optical, and electronic materials for advanced defense systems. During the period 1974-76 he served as a member of the U. S.-U. S. S. R. Bilateral Exchange Program in Magnetohydrodynamics and organized and was principal investigator of the MIT Fusion Technology Program. In 1970 Dr. Bement joined the faculty at MIT as Professor of Nuclear Materials and developed academic and research programs in support of advanced energy conversion technologies. With the change of contractor for the Hanford Laboratories from General Electric to Battelle Memorial Institute by the AEC in 1965, Dr. Bement advanced through a series of management positions to Manager of the Fuels and Materials Department, 1968-1970. He began his professional career in 1954 as a research metallurgist and reactor project engineer with General Electric at the Hanford Atomic Products Operation. Dr. Bement earned a B.E. in Metallurgy at the Colorado School of Mines in 1954 and advanced degrees in Metallurgical Engineering (M.S., U. of Idaho, 1959; Ph.D., U. of Michigan, 1963). Dr. Bement is a fellow of the American Nuclear Society, American Society for Metals, and the American Institute of Chemists.

The Need to Document Program Payback

"If You Use It, Tell Us!"

This special issue of the ManTech Journal for the 12th Annual Manufacturing Technology Advisory Group Meeting offers a unique opportunity to reach a broad range of the DoD Manufacturing Technology Program (MTP) community—both military and civilian. This community is familiar with the broad scope of the day to day problems of American industrial life—inflation, high interest rates, shortages of materials, long lead times, and high energy costs, just to name a few. Most of it is also familiar with a problem which does not press them specifically each day but which is slowly building up pressure and could cause long term, serious harm to the nation—the slow rate of industrial productivity growth of the United States relative to that of our international competition. Conscious awareness about this problem is also slowly occurring outside the industrial base and by the American public in general.

However, many still remain complacent about it because our high standard of living reflects that in absolute terms we are still the most productive industrial nation in the world. But we may not be on top for long! Our industrial competitors in the world markets are increasing their levels of industrial productivity at faster rates than we are

and one or more of them may soon exceed us in absolute productivity levels. Over the long term, unless these trends are modified our standard of living and our ability to defend ourselves as a nation will suffer. We need a strong, modern, productive industrial base to compete in world markets and to defend this nation.

The DoD MTP community is aware of this problem, for the contemporary literature has repeatedly provided facts supporting these trends. The question is: **What is being done about it?**

A Major Program Management Goal

The MTP is a key initiative directly aimed at this problem. The MTP is a major initiative intended to improve the productivity and responsiveness of the defense industrial base. Many have suggested that the MTP is an example others should follow. Yet others have said, "I hear you; but show me just how much you're improving productivity and reducing the cost of DoD's weapons systems?" Some of our answers to that question need to be strengthened. The main point of this article is that the MTP community (military and civilian) needs to strengthen the documentation of where project results are being implemented and the value of benefits being derived from that implementation. In short, the MTP community must document the return on MTP investments. It must demonstrate that the MTP is paying its way in terms others will understand. Strengthening this aspect of the management of the MTP is one of our major program management goals.

The importance of this aspect of the MTP was highlighted in the Statement of Principles agreed upon and signed early this year by both Deputy Under Secretaries of Defense for Research and Engineering and all three Service Assistant Secretaries responsible for the MTP. The SOP is reproduced inside the front cover of this issue. A key element of the SOP suggests that an ROI consciousness be developed and maintained throughout all levels of management. A second key element requires that the MTP be evaluated and payback demonstrated in unequivocal terms.

Services' Approaches Differ

Each military department has been asked to establish procedures to routinely document implementation of project results and benefits that have been achieved. They are following two basic approaches. The Army and the Navy are surveying industry one year after project completion and will document implementation/benefits identified. The Army has established a data base to keep track of this information. The Air Force is using a different approach which requires their new contractors to identify whether or not they have implemented results of a list of previous MT efforts identified by the Air Force. Neither of the two approaches have been in place long enough to evaluate their effectiveness and their pros and cons. The Army's first implementation/benefits report is scheduled to be available by the time of the MTAG Annual Meeting.

Thus, we apparently have the problem solved. But it is one thing for the services to agree to collect this information and it is quite another for them to do it effectively. The very nature of the technology transfer and diffusion process tends to frustrate even the most well intended project tracker. At the very basic level, the output of the MTP is information—whether it be embodied in a paper, a report, a film, or a magnetic tape. In all of these forms it can easily be passed along time and time again through several tiers of communication. The DoD is never sure who has the results from the MTP nor, more importantly, who is actually using them in one form or another for some benefit. What's more, other than in very few cases, no one is under any obligation to tell the DoD they have used the information. Thus, a corollary to the main point of this paper is directed primarily at our private sector colleagues; if you use the results from the MTP, tell us about it.

Size of Task to Double

Just how large is the tracking problem? Figures 1 and 2 show the total DoD and each service's funding for a ten year period (data as of July 1980). During the period from FY 77-81, DoD invested roughly $640 million in the MTP. Our plans call for nearly double that or nearly $1300 million during the next five years, FY 82-86. While one could select several values for an average size MT project, depending upon his assumptions, data from a recent Army report indicates their funded efforts average roughly $450K/year/project. Using this as a basis, DoD will support 2800 projects during the

next five years. By deleting multiple year efforts, one could assume 2000 projects over five years, or 400 per year. Thus, the procedures established must be capable of tracking this volume of effort.

If one knew the names and addresses of twenty people who knew the results of only one project, it would be a large task to survey them each year to ask if they had used the project results and, if they had, what the benefits and payback had been. One might expect some short, direct answers.

Thus, it may appear that the job is impossible. Clearly, it is not—for I will illustrate by means of examples how MTP payback can be documented.

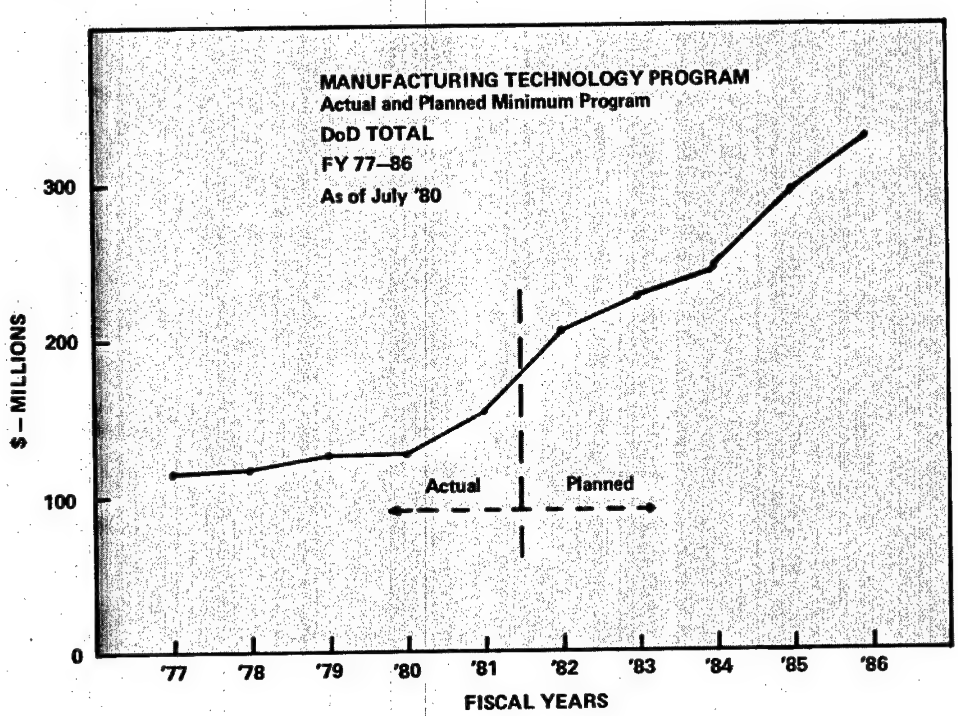


Figure 1

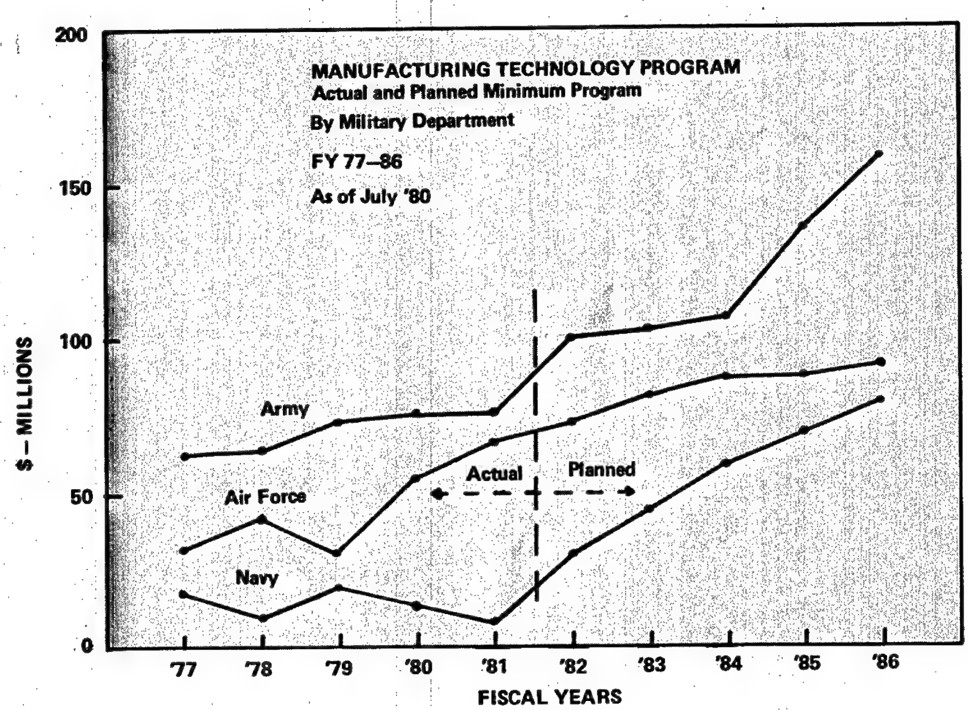


Figure 2

Tenfold Payback

Several years ago the Army became concerned over the cost of a titanium compressor housing for the T700 engine. Its method of manufacture consisted of forging two halves of the housing, machining both halves to the correct size and then welding and bolting the pieces and accessories together. The Army invested MTP funds in a new approach employing precision centrifugal casting of the housing. The project was a technical success and the new approach reduced machining by over 30 direct labor hours per unit. It also reduces the use of high cost titanium, for the casting weighs only 30 pounds while the forging weighed 65 pounds (See Figure 3). The original prediction of a 20 percent manufacturing cost savings on the component has been verified. While the total savings will vary based upon the number of engines eventually produced, it is estimated to be at least $5 million over the production life of the engine. The project cost was one half million dollars.

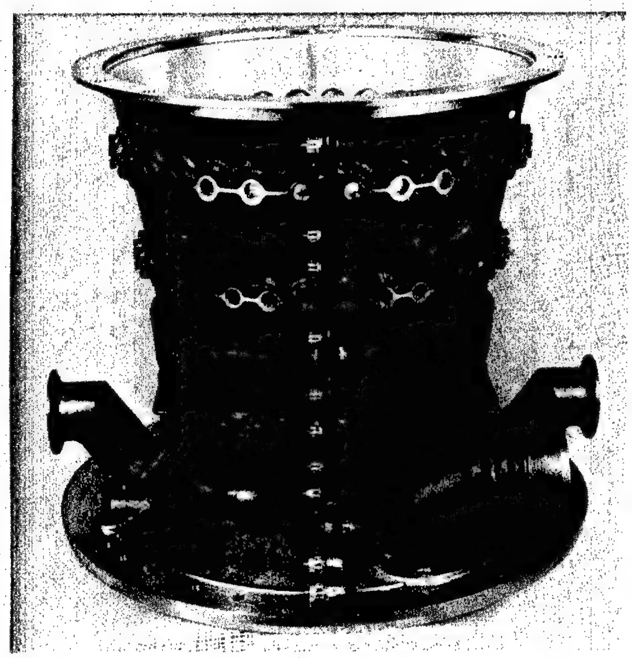


Figure 3

Near Net Shape Ti Channels

A similar success story has been reported by the Navy, dealing with the fabrication of titanium channels for aircraft structural application. Titanium is not the easiest material to fabricate. The original approach was to machine the channels from plate stock. The final 22 pound part was produced from a 240 pound plate by brute force, hog out methods. The next approach involved machining and electron beam welding two "L" shaped extrusions initially weighing 90 pounds. The Navy then invested in an approach to provide near net shape channels from titanium sheet stock by shaping the material between refractory metal rolls using progressive localized heating of both the rolls and the workpiece. The method is especially suited to high aspect ratio (long and narrow) shapes. It has been shown to reduce scrap by 50-90 percent and reduce lead time from 80 to 24 weeks for structural parts, while simultaneously reducing the cost of capital equipment necessary to do the job. In the example cited above, the rolled part weighed only 39 pounds (see Figure 4). Navy invested roughly $750K but estimates savings of over $6 million on only two major aircraft procurements.

HIP Improves Casting Properties

Payback from an Air Force MT project has produced similar results in the overall production base. In turbine engines there is always a natural tendency to want to use cast parts instead of forgings, for castings in general lower costs. However, castings typically have lower physical properties (by as much as 50%) and have a wider range of

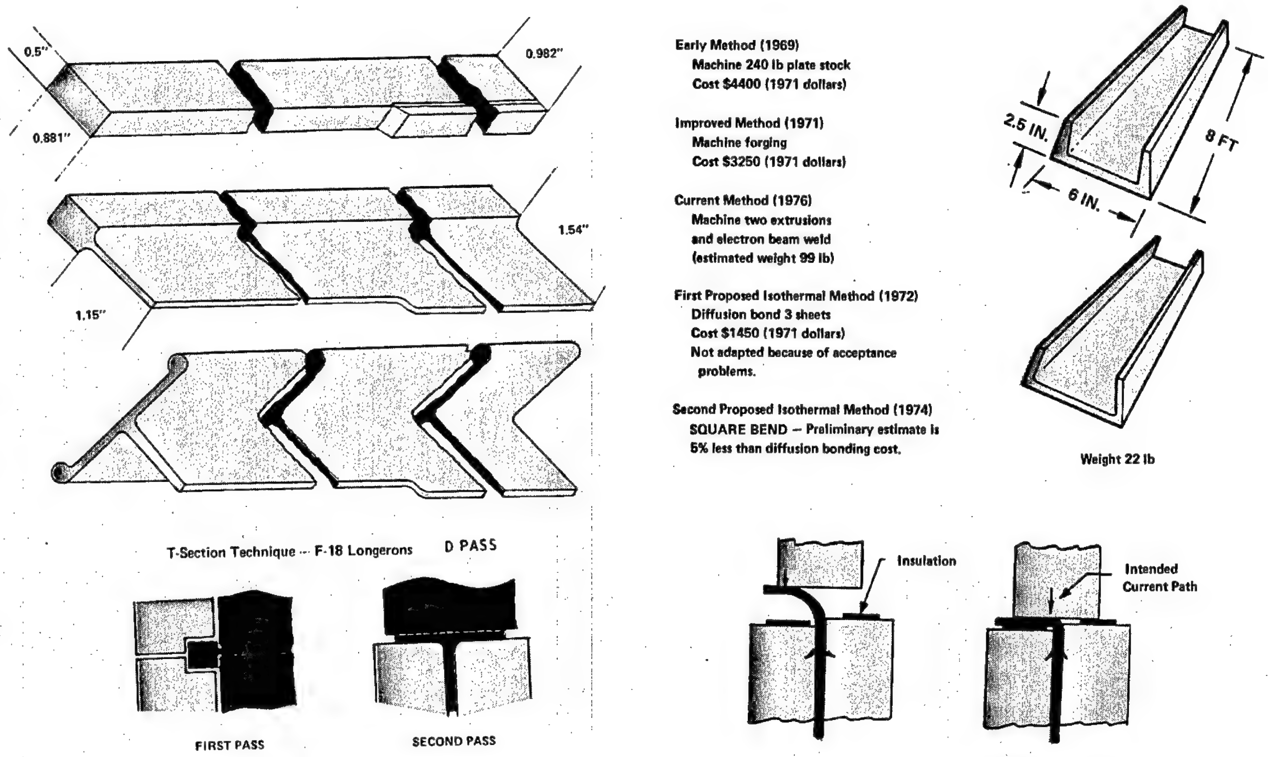


Figure 4

properties than forgings. However, castings can be produced closer to net shape and thereby save high cost/scarce materials and machining costs. A method was needed to improve the properties of castings.

The Air Force invested in a hot isostatic pressing (HIP) casting densification (materials property improvement) process applied to jet engine turbine blades. In essence, the cast blades are put into a pressure vessel where they are subjected to high pressure and temperature over a period of time. The resulting casting properties are improved

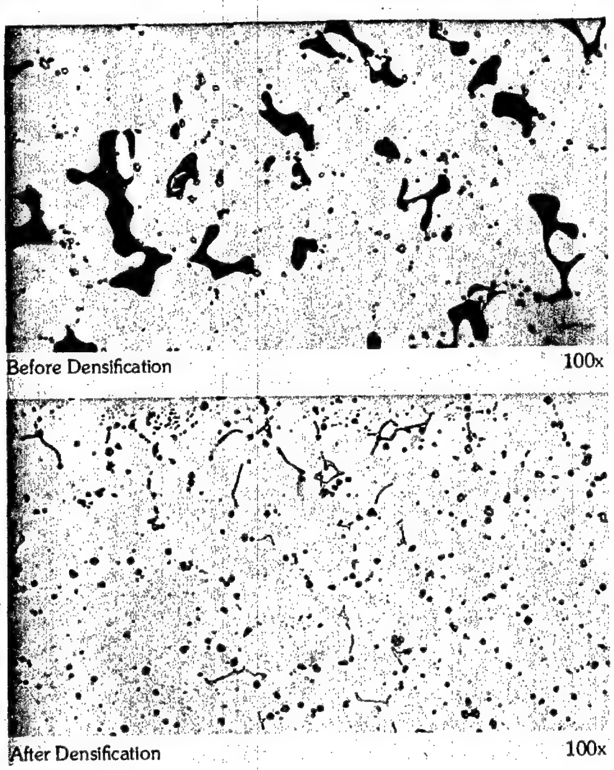


Figure 5

to the point where they can compete successfully with forged blades—and at a much lower cost. To date, over twenty HIP units are in operation in the industrial base and over 200,000 cast turbine blades have been processed (See Figure 5). One major blade supplier estimates his savings at $1.5 million/year.

Laser Drills Holes Easier

The Air Force also has had success reducing turbine blade costs by utilizing laser drilling to produce blade cooling holes (See Figure 6). These 0.008 to 0.050 inch diameter holes at depths of up to 0.750 inch would be difficult to produce in conventional materials, but are even more difficult to produce from high hardness blade materials. After completion of two MT projects, laser drills have been and will continue to be used in routine production. They reduce drilling costs from 20-90%, depending on the blade design; one contractor estimates his savings at $1.5 million/year. In addition, the maturation of the process will permit new design concepts for turbine blades to be evolved.

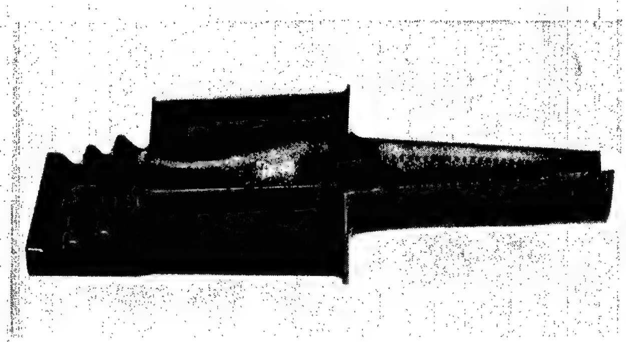


Figure 6

Foam Filled Radomes

The range of the scope of the MTP is very broad, and many varied materials and processes are candidates for cost reduction. For example, the Navy invested in a new process to substitute foam filled radomes for honeycomb structural radomes. The honeycomb units required a heavy capital outlay for autoclaves, vacuum systems, bonding presses, and high cost tooling and material. An R&D effort demonstrated the feasibility of using foam filled radomes which offered a 20:1 cost savings over honeycomb while retaining excellent transmission characteristics and superior weather resistance (see Figure 7). The MTP investment reduced the cost of PHALANX radomes by an order of magnitude. The $116K investment saved $405K on FY 78 procurements and is expected to save over $4 million more on scheduled Navy procurements through 1984. The same processes are applicable to similar radar applications in all three services.

Detonator Loading Automated

Perhaps one of the greatest areas of MTP savings is in the ammunition business. In this area, even a small unit cost savings can amount to millions of dollars quickly because of the volume of ammunition produced. One case in point is an Army investment in automated detonator loading. Production is measured in millions of units per month at peacetime rates and an order of magnitude above that for mobilization rates. AUTOMATION IS A MUST. The Army invested roughly $640K in a new automated detonator loader and the device increased production by over 300% per shift (see Figure 8). It reduced mobilization facility requirements by one complete facility, with the attendant cost avoidance of over $30 million for construction and equipment and a current operating savings of over $40,000/month at peacetime rates, with a corresponding greater savings at mobilization rates. In addition, the device enhances personnel safety by sharply reducing the number of people exposed to explosives during the loading process.

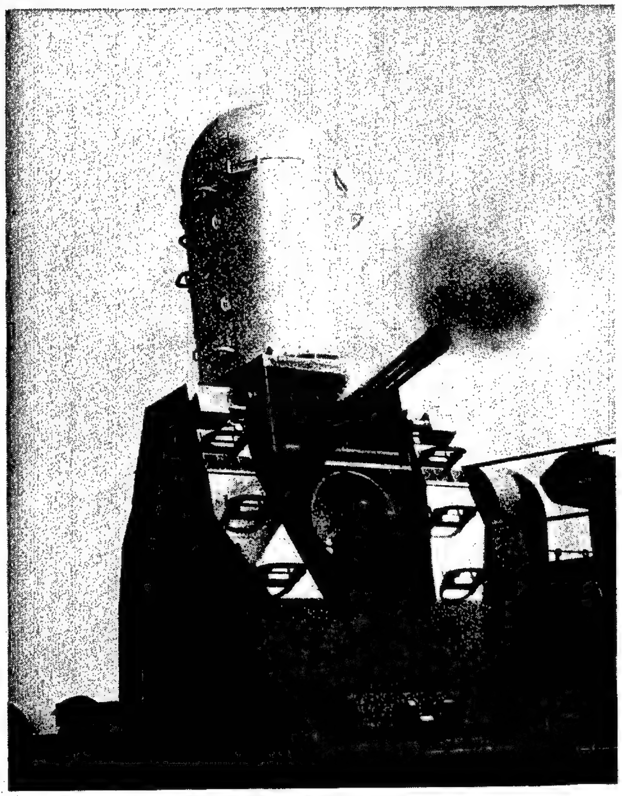


Figure 7

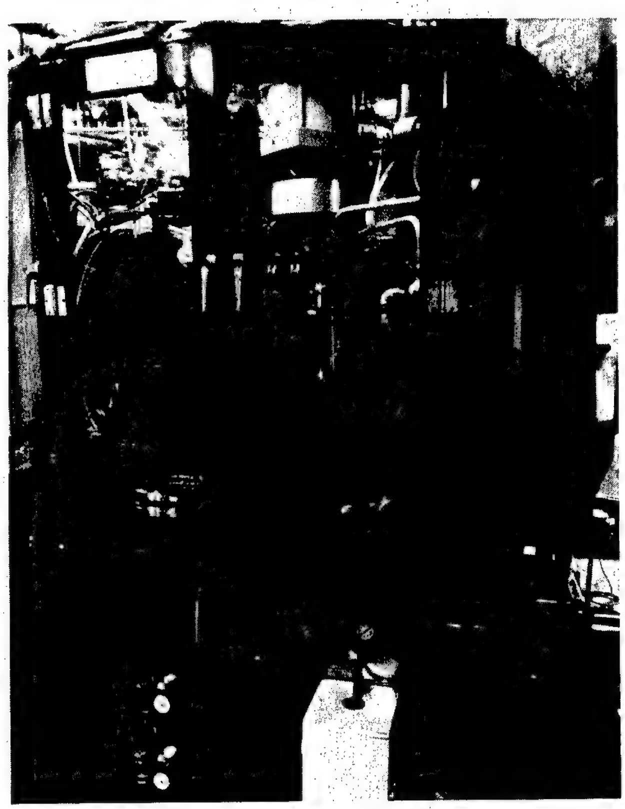


Figure 8

Timely Data, Cooperation Needed

The six examples cited above are illustrative of the roughly thirty examples of MTP payoffs presented to the MTAG Executive Committee last spring. The individuals responsible have a right to be proud of their contributions. These cases illustrate that tracking and documentation of implementation and payback can be accomplished if these key elements are in place:

(1) Everyone in the DoD MT community understands that payback documentation will be required from the onset. This will motivate every level of management to establish procedures to make sure that data is collected in a timely manner rather than helter skelter in a catch up mode two years after the fact.

(2) The private sector is provided the rationale for (and fully appreciates the need to positively respond to) MTP managers' requests for information. Success stories are equally as welcomed by private sector managers as by the DoD.

Project Followup A Responsibility

In summary, there is a need to strengthen the payback reporting procedures of the Manufacturing Technology Program. It is a stiff challenge, but it can be met if we as managers of the industrial base motivate ourselves and inspire our colleagues to develop an ROI consciousness and to always remember that project followup is an essential part of program management. The citizens of the nation will invest over one billion dollars in the MTP in the next five years. A one billion dollar investment can have a very positive impact on the nation's industrial productivity and on the nation's defense. It is our responsibility to report back to the citizenry how wisely we have invested their money.

Improving Productivity Through ManTech

JOHN LARRY BAER joined the Office of Manufacturing Technology at the U. S. Army Material Development and Readiness Command in September 1976, bringing with him over 24 years of experience in advanced material development. After serving at Picatinnny and Frankford Arsenals and at the U. S. Army Limited War Laboratory, he became Chief, Advanced Concept and Technology Division at the Small Arms Systems Agency in 1969. He took over the Weapons Systems Synthesis Division in 1971, headed the LWL Chemistry Branch in 1973, and was part of AMSAA R&D Field Liaison Division prior to joining Headquarters, DARCOM. Mr. Baer holds a Bachelor of Chemical Engineering Degree from CCNY, a Master of Science Degree in Chemical and Industrial Engineering from Iowa State, and a Master of Business Administration Degree from Temple University. He is a registered professional engineer and a recipient of the Army Meritorious Civilian Service Award. Mr. Baer served as acting chief of the OMT from June 1978 until January 1979 and now directs its Chemical and Mechanical Engineering Division.

Documentation Tells the Story

United States defense firms are operating with a shortage of skilled personnel, aging equipment, and constantly growing requirements for occupational safety and health and for pollution abatement. They are facing accelerating competition from overseas by dedicated workers, new and efficient machinery, and growing export demand. These problems can be offset by our improving productivity through development and use of the latest manufacturing technology concepts and principles, which are within our grasp through the Army's manufacturing technology program.

Manufacturing methods improvement has been the key to increased productivity since the beginning of the industrial revolution. However, a centralized Manufacturing Technology (MT) program for the defense establishment, as outlined elsewhere in this issue, is less than 17 years old. In this brief review, we will cover the Army's approach to and objectives for the MT effort and summarize several of the most significant projects.

A major impetus for the Army's MT program came from the 1975 guidance of then Deputy Secretary of Defense Clements. His direction was for a centralized office to manage the transition from hand crafted development models to low rate initial production of all Army commodities by identifying and exploiting MT cost reduction opportunities.

Utilization

The scope of the Army's MT thrust is illustrated by the list of commodities and technologies of interest in Figure 1. Note that present program emphasis is on end item development—i.e., MT projects should be directed toward increased productivity of a specific item and only secondarily to more generic applications. However, spinoffs applicable to other commodities will obviously result. The Army's MT Office provides the expertise for effective program management in all those areas listed. However, success of the program depends largely on the MT offices and project engineers in the

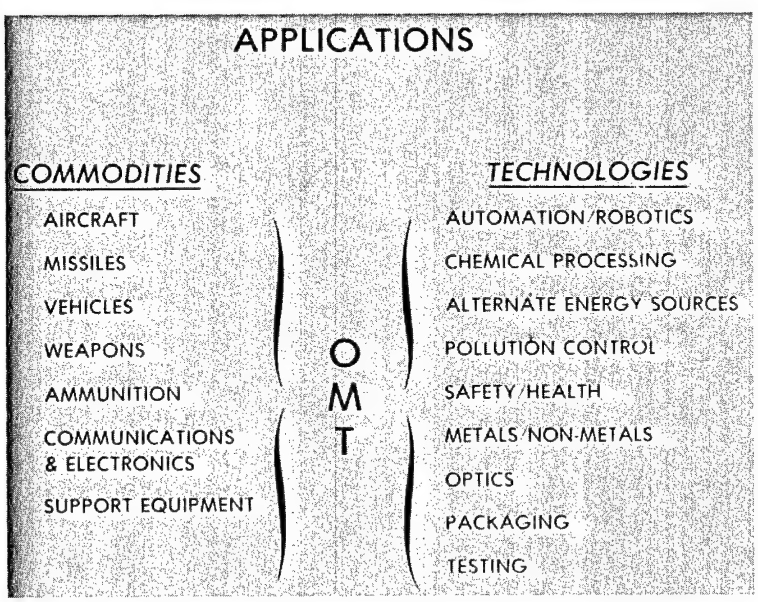


Figure 1

field and their counterparts in industry. The generation of project proposals and the performance of MT projects—whether the fruit of Government engineers or the product of industry—are, however, only precursors to implementation.

Unless they are effectively utilized, the results of MT projects are like wax fruits in a basket—ornamental but not nourishing. However, just how well they are utilized is sometimes hard to determine. Like a wholesaler, the Army can usually trace the project only to the first buyer. The flow of MT projects from concept to execution is illustrated in Figure 2. Working through the Industrial Base Engineering Activity (IBEA) and the Manufacturing Technology Advisory Group (MTAG), the Army is now attempting to document first applications and, through followup reporting, to trace additional implementations.

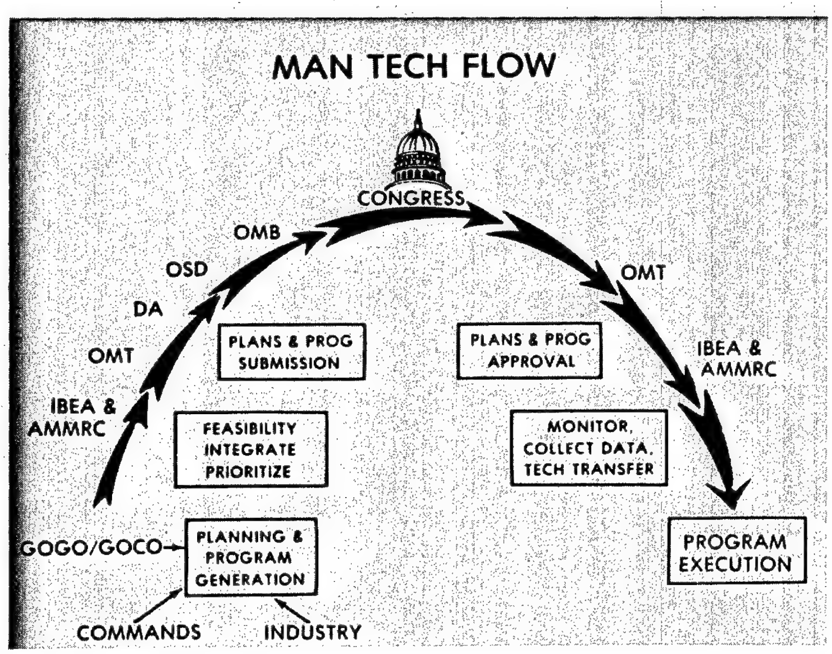


Figure 2

These reports will become a part of the Army's MT Management Information System, illustrated in Figure 3. Here, industry cooperation in careful reporting and documentations of results becomes important. IBEA can only ascertain whether the technology transfer seeds have fallen on fruitful soil if industry adknowledges its utilization of these tax supported MT project results. Hopefully, readers of this article and those who will hear this message at many symposia will heed this call for implementation reports.

Constraints

Along with the thrust away from extensive program planning review and toward

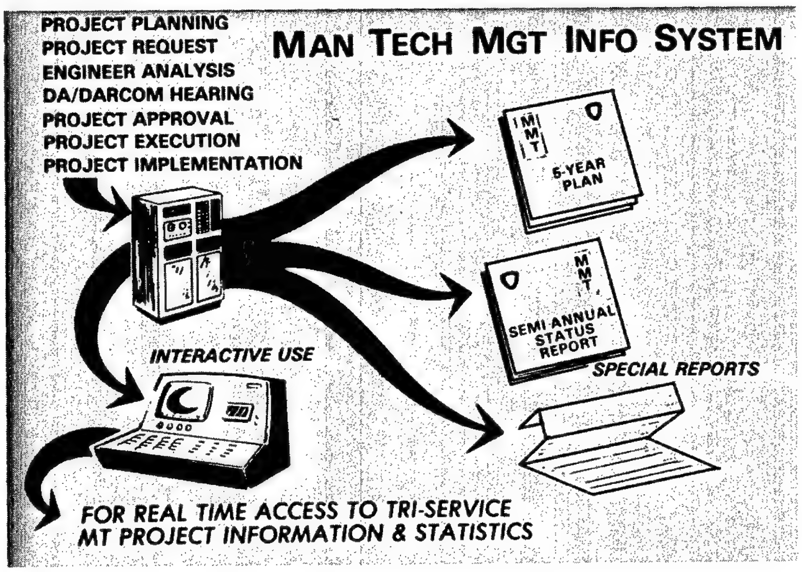


Figure 3

greater emphasis on implementation, we must recognize that the MT program is evolutionary, not revolutionary. Resources cannot pour directly into improved producibility. As seen in Figure 4, there is a valve in the line controlled by certain constraints. The real need is to assure our readiness for manufacturing military hardware from a warm or laid away cold base with minimum lead time and to reduce production costs for increasingly complex materiel in the face of shrinking budgets. However, the MT program faces serious restraints in safety and health regulations, pollution abatement requirements, and the urgent need to conserve energy and critical raw materials, frequently with less than skilled workers.

The Army's MT objective is to develop and implement manufacturing processes that emphasize energy efficiency, pollution abatement, and computer control. Although necessary, program improvements in safety, energy, and pollution hardly seem to be the stuff of enhanced productivity (the ultimate MT goal) or quantifiable cost benefit. Yet, in most cases large savings are clearly evident and without many of these MT projects to date production could have been completely halted pending conformance to the appropriate regulations. Most savings in the manufacture of Army procured materiel have been achieved through the design or adaptation of special purpose equipment, processes, or material. A goodly amount, however, has resulted from reduction of needed resources, such as raw material, water, or energy. Let's consider some of the past programs.

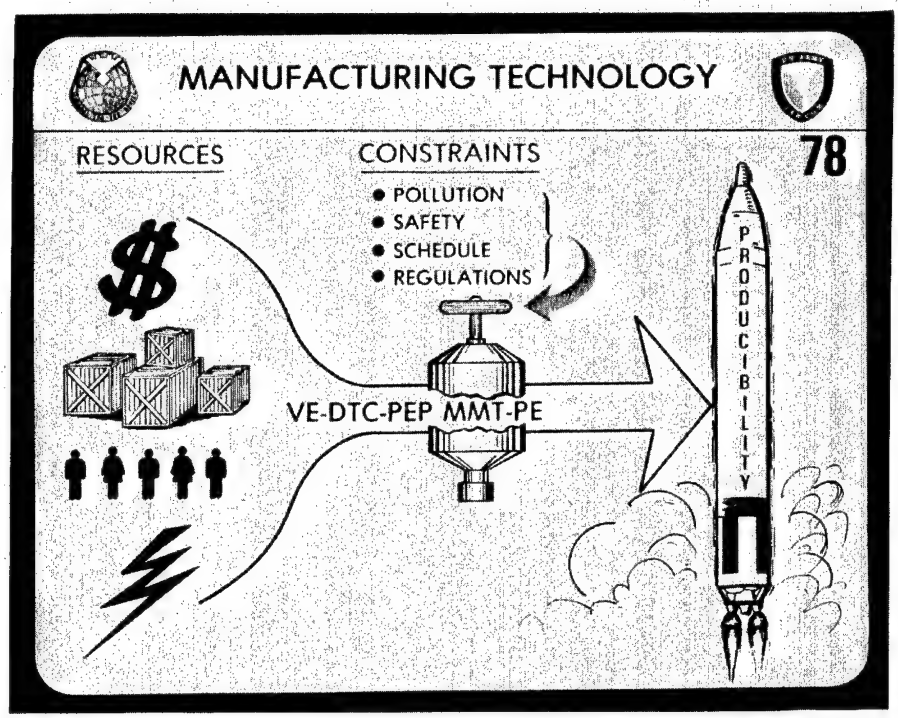


Figure 4

Forming Developments

Development of hot isostatic pressing for near net shape forming probably has the broadest application to the array of Army commodities supported through the MT program. Savings on the Army's T700 turbine engine alone are estimated at $3.7 million. Parts have improved low cycle fatigue. An adjunct process, isothermal powder metal forging, has demonstrated threefold improvement in material utilization (and hence vast reduction in scrap) and has reduced the number of machining steps by 50 to 65 percent. As a result, 50 percent cost savings have been realized through MT programs for items from simple vehicle yokes to precision turbine blades and vanes. The potential for enhanced, low cost producibility with this process is limited only by the ingenuity of the designer and production engineer.

In a completely different vein, consider a way in which water was saved through an MT project. The arrangement for effluent handling at Radford AAP not only provided a nice cost avoidance because an $11 million water treatment plant didn't have to be built, but it cut daily water consumption tremendously—from 3.3 to 0.3 million gallons per line. Of course, it drastically curtailed downstream pollution and, as an extra benefit, allows recovery and reuse of 32,000 pounds of salts daily that would otherwise have been washed down the river.

Energy Savings Through Value Engineering

Value engineering is an adjunct to MT efforts that is usually invoked on production processes. Figure 5 illustrates how energy was conserved by utilizing waste heat during nitrocellulose manufacture. The luxury of cheap energy is a thing of the past; the profligate energy consumption in our country at a per capita rate twice that of European nations can no longer be tolerated. We have neither the nonrenewable energy sources to waste, nor can we recklessly pump the waste heat or its concomitant particulate and gaseous pollutants into the atmosphere. Whether through value engineering or through novel MT adjustments to the manufacturing process, we must modify our ways in order to pass on a viable biosphere to the next generation.

Engineers at Watervliet Arsenal demonstrated that a little ingenuity can go a long way to replace the 40 hours of tedious hand filing needed to remove sharp corners in the bore of 152 mm cannon tubes with 2 hours of simple mechanical abrading, using nothing more than a glorified dentist's drill. Similar automated finish grinding jobs, called benching, not only overcome such tedious hand work but also remove the health hazard created by the fine particulate generated as a gun breech block is honed to the fine fit demanded of it. For a project cost of $35,000, the total savings through 1977 were $2.5 million.

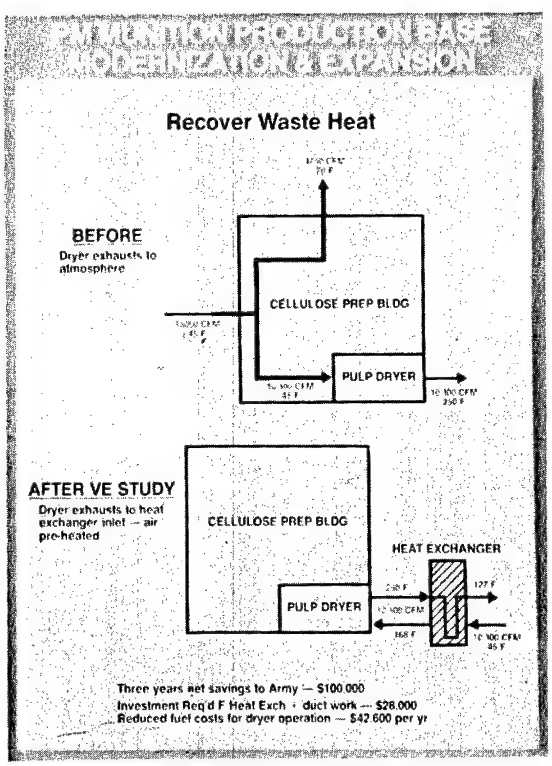


Figure 5

Simulated Test Firing

As the result of an MT program at Rock Island Arsenal, the loads applied on artillery recoil mechanisms and carriages by live firing are now simulated with an impulse generator developed at a cost of $525,000. The load is applied by firing just $3 worth of powder rather than $168 105mm or $256 155mm rounds. And the simulation of applied loads does more than save money and time. This arrangement, which has saved the Army some $12 million in the 8 years it has been in use, also does away with the need for having special ranges, for shipping the gun to such ranges and back for proofing, and for all the labor and paper work connected with such a procedure. Such large scale simulation, carried out to test the effectiveness of our production processes, has application in many areas.

In another program, equipment was developed at a cost of $250,000 for automated inspection of precision fuze parts. This equipment can evaluate the precision with which fuze parts are made much more accurately and rapidly than the human eye ever could—and without fatigue and the deteriorating quality of inspection that goes along with it. It provides printouts of results and can be used for 100 percent inspection when needed. The technique is adaptable to a variety of parts and has already paid for itself many times over.

Cost Driver Analysis

There are two areas where enhanced mechanization of production is critical to improving productivity. The first is in the manipulation of parts that are either so small as

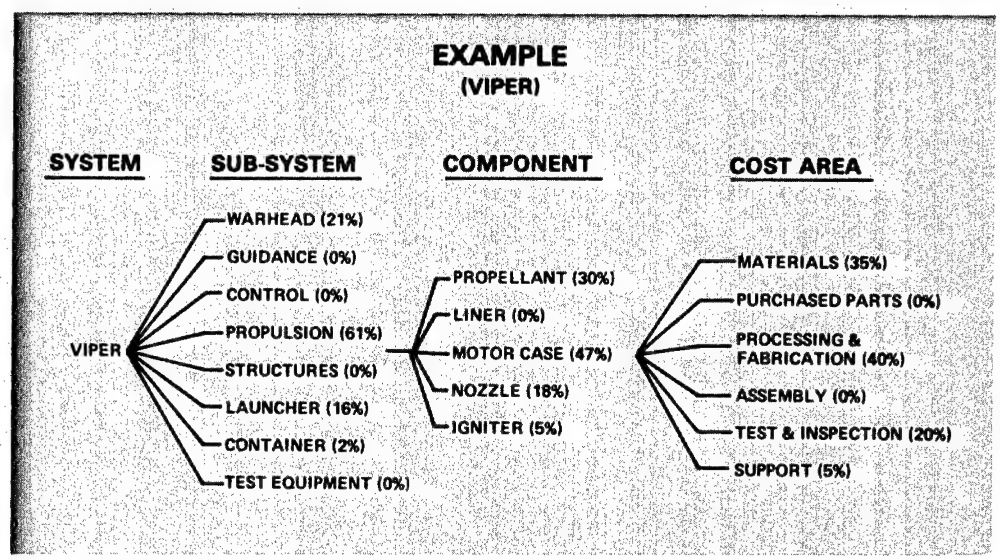


Figure 6

to try the manual skill of the artisan or so large as to require extensive power assist—as for example with large caliber gun barrels or tank hulls. The second is in areas where a cost driver analysis, as illustrated for the Viper missile in Figure 6, has identified a part as contributing a disproportionate percentage of total system cost. Where size or complexity are not self evident justification for mechanization, a cost driver analysis will identify where MMT dollars can be wisely spent. With limited funds, we cannot afford to fritter them away on tasks of limited utility or marginal productivity increases.

Sensing various process parameters can be a critical part of a manufacturing process. However, sometimes even our mechanical aids, superior as they are to human senses, are no match for the pressures, stresses, and temperatures we must use to create the Army's materiel. Such is the case in measuring and controlling the heat input to smelting furnaces. Conventional instruments give only crude estimates of the temperature in or near a molten bath or a tempering furnace and have time lags built in that preclude swift correction of unnecessary overheating. The simple fluidic high temperature sensor shown in Figure 7 overcomes those shortcomings. Using readily available shop air in a ceramic anulus, it provides virtually instantaneous measurement of furnace temperature. This allows rapid adjustment so that no more heat than is absolutely necessary to treat the part or melt the pour is provided.

Development of Automated Systems

Automation frequently lets us do things much more efficiently than we can do them manually. The automated tape layup (ATLAS) of helicopter blades is a case in point,

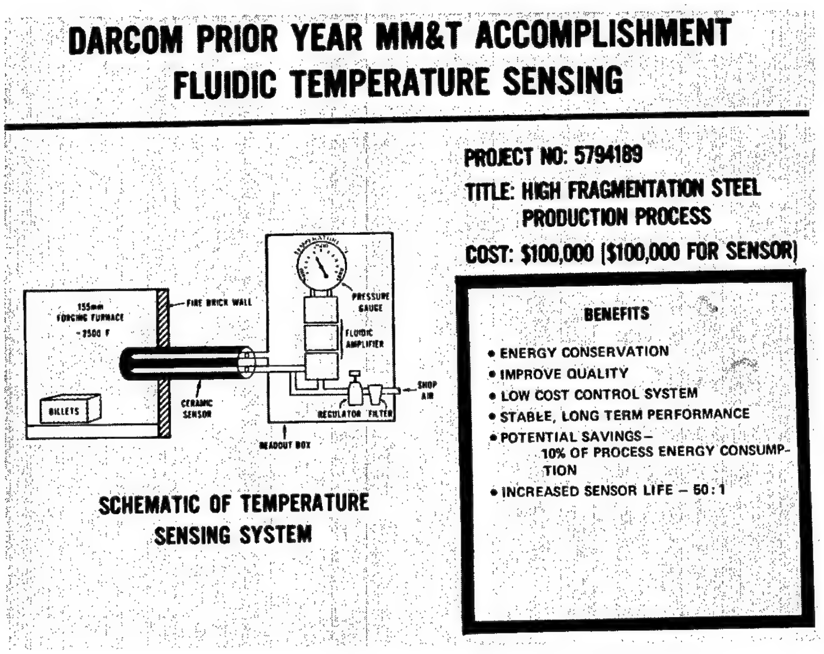


Figure 7

resulting in a cost reduction of $19,000 per blade. During MMT development of this process, a flexible 6 degree of freedom machine was used to demonstrate the potential effectiveness. The 2 degree of freedom machine ultimately used in production has all the necessary versatility to generate a blade with a life expectancy ten times that of the hand laid up version. It also permits field repair of bullet holes or other damage and, by virtue of the smoother layup, generates more lift. These are unexpected, but very welcome, benefits of this automation applicable not only to helicopter blades but also to missile bodies and similar structures.

The same type of process used to lay up helicopter blades automatically, evenly, and smoothly is being considered to replace the hand layup of plies for a helmet. This involves the random laying up of the reinforcing fibres onto a matrix. Merely by virtue of using a continuous fibre rather than cut strands, the helmet is expected to be not only more uniform, but materially stronger and more impact resistant for its weight than the hand laid up version.

Computer Control

A superior product is not always the driver behind MT projects. Sometimes it's the potential loss of certain skills in the labor force. Such a skill is reticle scribing in the manufacture of fire control instruments. Even with the pantograph, which permits simultaneous creation of ten uniform reticles, a sneeze or hesitation that mars one part mars all ten.

In an MT program, a computer-controlled engraver was developed to do this job. Applicable to reticles for binoculars, periscopes, telescopes, and range finders, it saves 60 percent of preparation costs and 50 percent of labor costs. Automated scribing can do the job faster, more uniformly and more reliably—hence more efficiently than the fast disappearing craftsman. Not only do we acquire greater productivity, we also generate a computer capability to fill in for the craftsman when he's sick, when he retires and there's no replacement, or, more importantly, if a sudden mobilization requirement overloads the available capacity.

Computer controlled manufacture on a much larger scale was developed during the Small Caliber Ammunition Modernization Program (SCAMP), which involved automation of the complete production, testing, and packaging facility. Automation, at a cost of $18 million, has eliminated over a period of 8 years the crude methods, the dirt, the waste, and the human wear and tear needed to make small caliber ammunition in the past. SCAMP doesn't produce the small caliber ammunition as cheaply as predicted yet. But when the rent and overhead have to be paid to produce 5 to 6 million rounds per month on a machine system designed to operate at a minimum rate of 7 million rounds, price has to be sacrificed until the system can be brought up to speed and is completely debugged. The productivity enhancement potential is irrefutable, with projected savings of $45 million over 10 years when the lines are fully operational.

Long Range Planning

This gives you some idea of the scope of Army MT efforts and the significant accomplishments to date. With the improved MMT project monitoring provided by the MT Management Information System at IBEA, the Army can now pay closer attention to tracking and implementing successful MMT projects and at the same time improve future planning. Figure 8 shows one approach to long range planning.

The productivity growth picture, so dismal for the U. S. overall, is really fairly good in the manufacturing sector, which was able to boast an annual 1.7 percent growth rate for the years 1973-78. Even while the non farm business sector productivity has

declined steeply, the productivity in the manufacturing sector of the economy managed to rise at an annual rate of 3.3 percent during the 3rd quarter of 1979. It is factors like these that have caused foreign firms like SONY to build plants in the United States, citing lower transportation and raw materials costs and lower utility and tax rates than in Japan as incentives, as well as **good worker productivity**. While Japan, France, Sweden, the United Kingdom, and Germany are fast approaching U. S. productivity at growth rates exceeding ours, they still lag behind our industrial productivity in terms of output per man-hour.

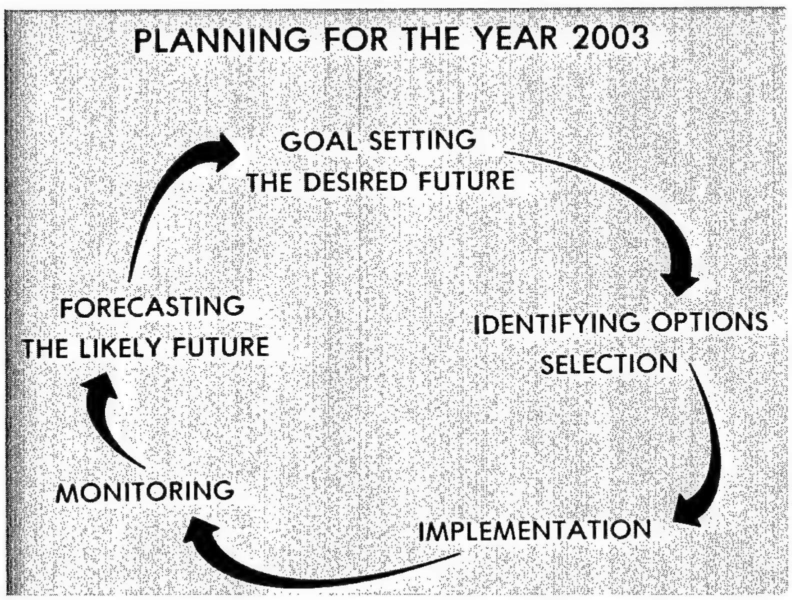


Figure 8

MT Budget Forecasts

As indicated in Figure 9, the forecast for the Army MMT budget is one of modest increase commensurate with modest growth in procurement of military hardware. However, this budget will permit the funding of many worthwhile projects in both government laboratories and to a greater extent in private industry. Peacetime savings over the next 5 years from MT projects already completed are estimated at $530 million. A few individual projects, like ATLAS, have projected 10 year savings that would pay for the whole MT program over the last 10 years by themselves.

An area that can be expected to impact on MMT is international technology transfer. The U. S. cooperates, and at the same time competes, with industries in friendly, allied and maybe even "unfriendly" or third world nations. In an increasing number of areas, overseas industries have developed unique and often superior technologies that we

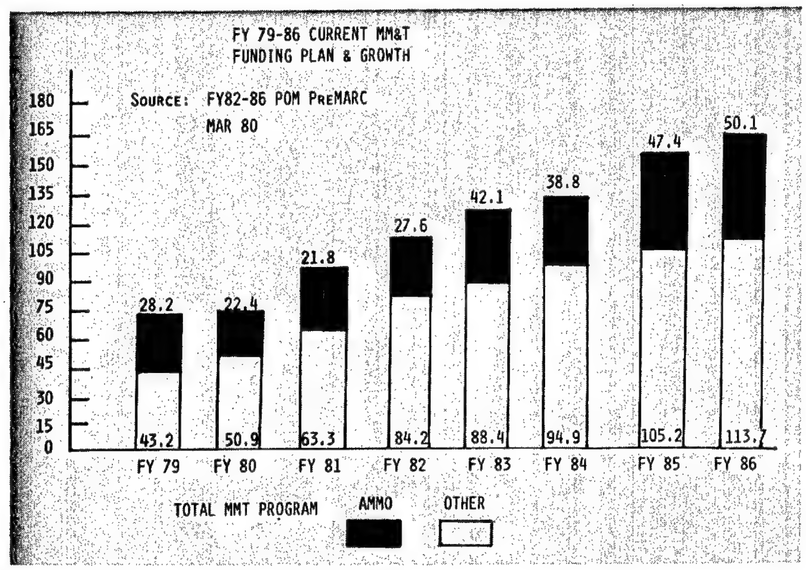


Figure 9

have eagerly adopted or are obliged to use. Examples are the Austrian Rotary Forge, Swiss Conicell NC Purification system, and Swiss carbide hobs. We must continue, for our national well being, to seek out and utilize the best foreign manufacturing technologies. At the same time, we have the moral obligation to share some of our technologies with our allies, while carefully scrutinizing and protecting critical technologies from inadvertent transfer to unfriendly nations through third country sales.

Implementation

In summary, the Army's MT goals are consistent with Congress' and GAO's concerns:

- Maintain close control on project selection and prioritization
- Follow up to ensure successful completion and utilization
- Improve implementation and its documentation through the implementation plan.

An implementation plan and road map are now required with all P-16 project proposals to cover the activity up to and through the final implementation follow-up. The Army will work closely with industry counterparts through the Manufacturing Technology Advisory Group and all its subcommittees for a stronger free world and a more productive America.

Navy MT Stresses Interaction

CAPTAIN FREDERICK B. HOLLICK, USN, is the Director of the Navy's Manufacturing Technology Program. He graduated from the U. S. Naval Academy in 1952 and served a tour of sea duty with the Amphibious Forces prior to entering the Flight Training Program. After receiving his wings, he served with various carrier based Anti-Submarine Warfare Squadrons. He attended the Navy's postgraduate school at Monterey, California, and after receiving a B.S. Degree in Electronics Engineering, served in Air Development Squadron ONE (VX-1) as a Sonics Systems Project Officer. Shore based tours included Project Officer of Shipboard ECM systems while on the staff of Commander, Operational Test and Evaluation Force; a tour at the Naval Academy teaching Electronics Engineering; and several tours in OPNAV involving RDT&E in the Tactical Air Warfare Branch and later in the Reconnaissance and Surveillance Branch. CAPT Hollick has been in his present assignment since October 1979.

Return on Investment of 6 to 1

The Navy considers Manufacturing Technology (MT) to be an important discipline with a demonstrated potential for reducing procurement and life cycle costs and for increasing productivity by establishing new or improved manufacturing processes for the production, overhaul, and repair of Navy weapons.

Directed At Cost Reduction

The Navy MT Program objectives center on reducing acquisition costs for material to support current and projected fleet needs. Specific objectives are to

- Reduce acquisition and life cycle costs of Navy systems.
- Promote and establish improved processes, methods, techniques, and equipment for the most efficient and economical production of defense material.
- Provide the technology required to advance manufacturing capability.
- Stimulate industry to implement and invest in new manufacturing techniques.
- Provide maximum dissemination of the results of manufacturing technology projects and promote early implementation.
- Strengthen the defense industrial base.

As shown in Figure 1, the MT Program is centrally managed by the Program Director under the direction of the Chief of Naval Material. The Naval Material Command Industrial Resources Detachment (NMCIRD), located in Philadelphia, provides technical review, technical coordination, and administrative support. Each Systems Command (Naval Air Systems, Naval Electronic Systems, and Naval Sea Systems) has a manufacturing technology office to support the MT Program Director. These offices are responsible for planning, executing, and implementing the portion of the MT Program that falls within their area of interest. The Navy Field Activities, such as laboratories and engineering centers, support the three Systems Commands directly through engineering efforts or contract monitoring.

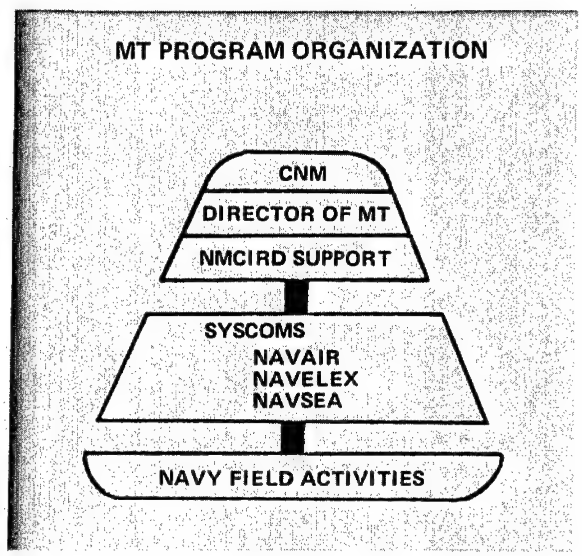


Figure 1

Proposals Welcome

Participation in the Navy MT Program is open to all. Both government and private sector involvement are required to meet the challenge of providing the necessary quantities of sophisticated new weapon systems under projected austere budgets of the future. Emphasis is placed on technological innovations that directly relate to defined Navy needs. As can be expected, the Navy will not support efforts that exclusively benefit the commercial market. However, technologies largely in support of defense requirements frequently have commercial application.

To provide a semblance of order to the input for this wide ranging program, there are some specific guidelines for manufacturing technology proposals. To be considered for funding support, projects should

- Satisfy a current or anticipated Navy need.
- Be designed to establish new or improved production and overhaul technology; the mere application of existing and proven technology is not sufficient cause for active consideration under this program.
- Involve a technology whose feasibility has been demonstrated at laboratory or higher levels and that shows a probability of success in industrial application.
- Not knowingly duplicate other efforts available or under development for Navy use on a timely basis.
- Be beyond normal industrial risk.
- Generally pay for themselves (self amortize) within a five year period, starting with the initial year of funding.

Designed For Interaction

Figure 2 shows how the organizational elements in the MT Program interact with themselves and contractors to generate projects in response to Navy needs.

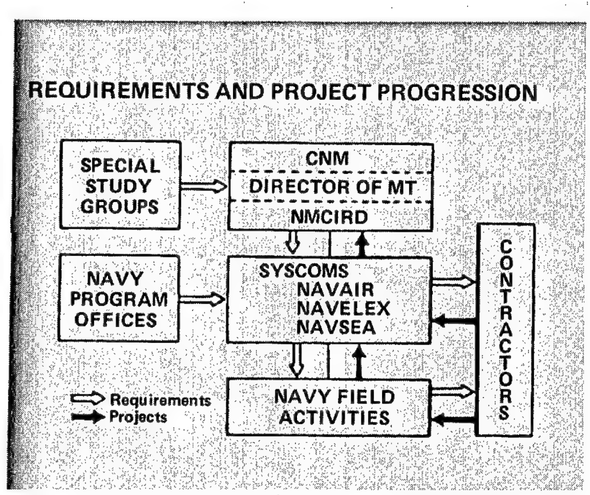


Figure 2

Program offices and special study groups are instrumental in generating technology requirements. Confirmed requirements are passed from the Chief of Naval Material to the Systems Commands for full verification and substantiation. Performing activities then define projects to answer those requirements—contractors play a very significant role in the program.

Review of project proposals is performed at several levels within the government. Navy coordination is conducted by NMCIRD and interservice coordination takes place through tri-service MTAG technical subcommittee meetings. Project approval and funding authority resides with the Program Director at Naval Material Command Headquarters in Washington.

The Navy has invested $57.0 million in its MT program, beginning with initial funding in FY 77. The potential return on investment of successful projects is estimated to be in excess of 6 to 1. However, this is based on a small sample size since only now are the FY 77 projects coming to fruition.

Two examples of successfully completed projects follow.

TORPEDO PROPELLER MANUFACTURE

A program was conducted to reduce the cost of manufacturing torpedo propellers by establishing production plastics molding techniques. In the past, propeller design specifications restricted manufacturing methods to machining. With the advent of the advanced MK46 (Neartip) torpedo propeller design incorporating various cost reduction features (fewer and thicker blades and blunter leading and trailing edges), it became feasible to investigate alternative manufacturing methods and materials to significantly reduce production costs. With the feasibility of molding plastic torpedo propellers having been established, an MT effort was launched in FY 78 to move the molding technique from the feasibility state to the production floor.

The cost of the MT effort, completed in April 1980, was $287,000. The cost of a set of machined Neartip torpedo propellers (two counter rotating) is $1500. The estimated cost of a molded set is only $360. Based on a procurement of 6300 Neartip torpedo propellers through FY 85, the estimated total savings are $7,182,000. This technology will be implemented on the next Neartip torpedo production contract.

GRAPHITE EPOXY SUBMARINE MAST

Submarine performance at periscope depth has traditionally been limited by performance characteristics of periscopes, antennas, and masts, which are extended for surveillance and communication. The majority of these masts have a circular cross section and produce excessive wake, vibration, and noise. Attempts to streamline them with retractable fiberglass fairings have met with limited success. Streamlining by different cross section design has been hampered by the designers' use of stainless steel and fiberglass. Insuring an adequate stress level in a mast made from these materials requires a large, bulky structure that negates the purpose of streamlining. In order to meet streamlining requirements, the **Dark Eyes** project is developing a titanium mast, which is both expensive and difficult to manufacture.

Therefore, it was proposed that the titanium be replaced with a composite material. Graphite epoxy is a high strength composite whose usage has advanced to the point at which more efficient production techniques are required. This material is extremely stiff and has a high strength to weight ratio, both highly desirable attributes in mast construction. Its use in this application offers large reductions in production costs. Considering these advantages, an MT project was initiated in FY 77 to develop manufacturing techniques for efficient, low cost fabrication of composite masts.

To date the cost of the MT effort is $403,000. It is estimated that the composite mast will cost only $28,000 compared to $70,000 for the titanium mast. Based on procurement of 42 masts through FY 86, the estimated total savings will be $1,760,000. This technology will be implemented on the next **Dark Eyes** contract.

Efforts Vital To Defense

If the Navy's forces are to be maintained at levels to sustain mission essential requirements, rather than what the Navy can afford, then Government and Industry must act together to best utilize available technology, capital and labor quality to attain those goals that best serve our country's defense needs. The manner in which the major elements are addressed—in particular, technological change—can strongly affect our defense posture through increased productivity.

The Navy Manufacturing Technology Program outlook is good and our experience thus far has been worthwhile. We look forward to improving our record and performance.

Mission Clearly Defined

Air Force Program Features "Top 10"

JAMES J. MATTICE is Director of the Air Force Manufacturing Technology Program managed out of the AFWAL Materials Laboratory, WPAFB, Ohio. Since assuming that position in 1974, he has been responsible for the planning, implementation and operating effectiveness of the technical, financial, and administrative management aspects of the AF Manufacturing Methods Program and the Computer Aided Manufacturing Program. Mr. Mattice received his B.S. in Chemistry from the University of Portland in 1958, did his graduate work in Chemistry at Ohio State University (1959-1962), and, under the AF Executive Development Program, attended Stanford University as a Sloan Fellow, completing that graduate program in Business Administration in 1968. He has served in several capacities at the Materials Laboratory, including service as Chief of the Chemical Processing Branch, Chief of Operations, and Assistant Chief of the Manufacturing Technology Division, prior to his present position. He has received numerous awards including the International Personnel Management Association and Dayton Area Chamber of Commerce Outstanding Supervisor of the Year Award in 1976, The AF Systems Command Certificate of Merit in 1978, and the Meritorious Civilian Service Award in 1979.

The ultimate goal of the Air Force ManTech Program is to achieve weapon systems' cost reductions in the acquisition, ownership, and support phases. A further goal is to provide for the maximum production efficiency of critical performance military hardware.

Major Accomplishments

All of these goals have been outstandingly achieved in the following "Top 10" Air Force MT Programs. The programs include the

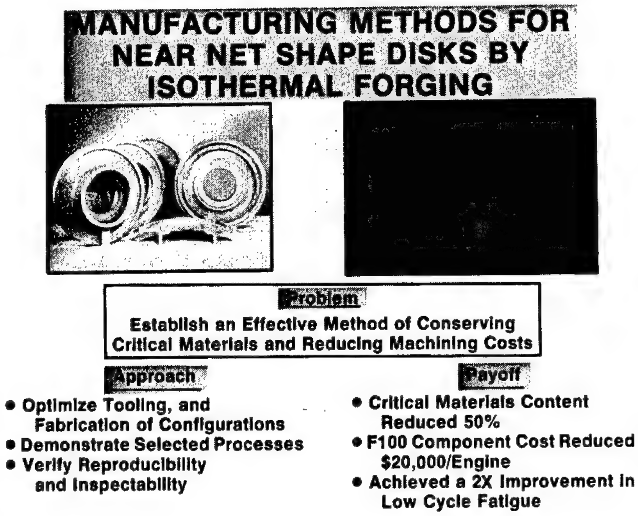
- Isothermal Forging of Near Net Shape Disks
- Automated Production of Hermetic Chip Carriers (HCC)
- Development of Quality Cast Aluminum Structural Components
- Fabrication of Zinc Sulfide FLIR Windows
- Hot Isostatic Pressing (HIP) Densification of Castings
- ICAM Robotic Sheet Metal Drilling and Routing
- Production of 30mm Armor Piercing Rounds
- Automated Fatigue Crack Inspection of Aircraft
- Engineering of Carbon-Carbon Nozzles for MX Missiles
- Modernization of F-16 Manufacturing Procedures.

Brief highlights of each of these programs follow.

ISOTHERMAL FORGING OF DISKS

The reduction of costs together with the conservation of critical materials were two key objectives in the development of manufacturing methods for near net shape disks by isothermal forging. Full laboratory qualification of the process via microstructural and mechanical property analyses was an additional goal.

These objectives were fully achieved with the development of a two step isothermal forging process capable of producing near net shaped configurations based on a 0.050 inch envelope over the finished part. The full scale parts forged were lighter than conventional one step forgings and responded well to heat treatment. The im-

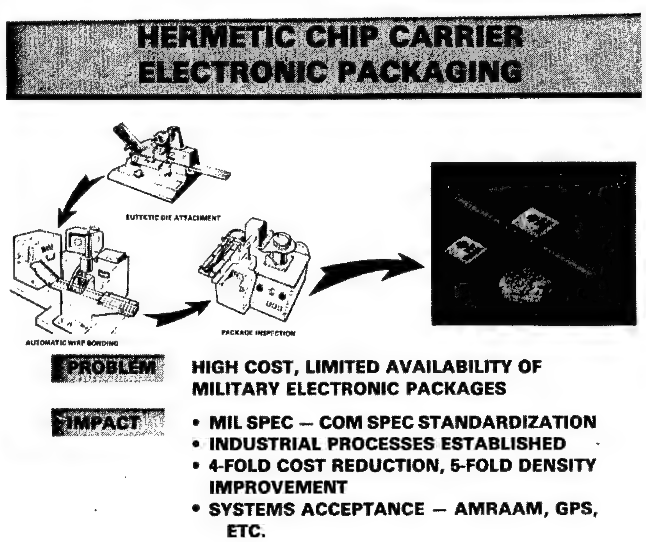


proved process resulted in mechanical properties significantly exceeding production specifications for the material.

A sonic inspection phase demonstrated the ability to fully inspect near net shape forgings through extension of state of the art transducer and pulser design. During this final phase a cost study revealed that $20,000 and 50 percent of the critical materials required were saved per F-100 engine upon complete incorporation of the two step isothermal forging process.

HERMETIC CHIP CARRIERS

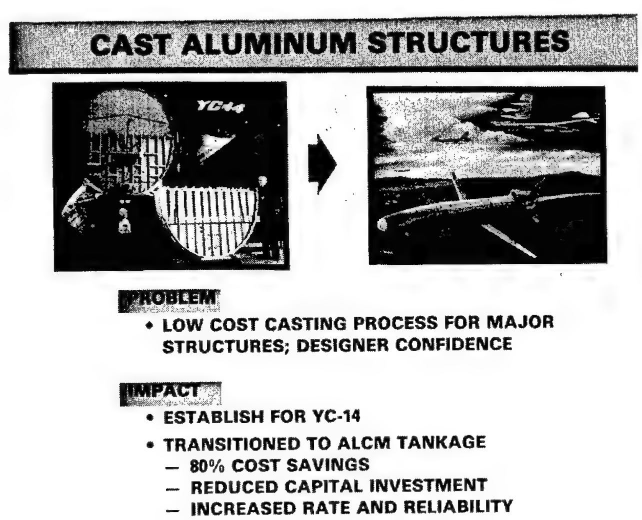
The Hermetic Chip Carrier (HCC) is a low cost, high density microelectronic package used in the interconnection and protection of integrated circuit chips. HCC packages permit the integrated circuit chip to be automatically assembled and functionally tested in a hermetic sealed package prior to further integration or interconnection in an electronic system. Potential system applications include the advanced medium range air to air missile (AMRAAM), global positioning system (GPS), and the Navy AN/UYK-44 standard computer.



A major key to cost reduction was determined to be high packing density combined with automated assembly and automated full functional circuit testing. The leadless HCC eliminates the cost of leads, the gold on the leads, and handling problems associated with leads. The use of chip carriers further results in a lower systems cost because the high packing density obtained with chip carriers requires less board and cabinet space.

As an example of typical cost savings, a central processing unit (CPU) built with all small scale integrated circuit chips fabricated in present commercially available dual inline packages would cost approximately $8,000. By contrast, the cost of a similar CPU with more compact circuit structure fabricated in HCC packages is $2,000.

CAST ALUMINUM COMPONENTS



The cast aluminum structural components MT Program successfully demonstrated the integrity, producibility, and reliability of cast aluminum primary aircraft structures. The program was undertaken as a direct result of the escalating costs of conventional aircraft fabrication methods.

The Air Force YC-14 body/nose landing gear support bulkhead was used as the trial component because of its high cost, complex shape, large size and primary structure. Twenty bulkheads were successfully cast.

The cost of the cast bulkhead was 38 percent less than the sheet metal buildup fabrication. In addition, the unit satisfied all durability, damage tolerance, and static strength requirements.

The YC-14 casting technology was utilized further to develop a new cast fuel tank concept. Estimates are that the new cast tank concept will dramatically reduce costs of this unit by some 80 percent.

ZINC SULFIDE FLIR WINDOWS

FABRICATION OF ZINC SULFIDE FLIR WINDOWS

CVD PRODUCTION FURNACE

PAVE TACK FLIR WINDOWS

MANUFACTURING TECHNOLOGY PROBLEM
- High Cost Of FLIR Windows
- Lack Of Industry Capacity and Capability

APPROACH
- Establish Production Deposition Capability
- Optimize Fabrication Parameters To Achieve Minimal Costs While Maintaining Required Property Characteristics
- Secure Industry Commitment For Production

ACCOMPLISHMENTS & IMPACT
- Scaled-Up Process From 2 To 24 Units/Batch
- Obtained Contractor Facilities Investment
- Reduced Costs From $22K Per Blank To $7K
- Implemented On PAVE TACK Production

An Air Force MM&T Program led to an increase in production capacity and cost reductions of large zinc sulfide windows for FLIR applications using the chemical vapor deposition process. Previously, only two windows per deposition run could be made. At the conclusion of the program, up to 24 window units could be fabricated per deposition run.

To achieve this success, a multiplate deposition system was designed and built. Also, process conditions for depositing the material were optimized, and quality control procedures were established.

Currently, window blanks are being fabricated on a production basis for PAVE TACK at a rate consistent with the program schedule. The cost of the blank has been reduced from $22,000 to under $7,000.

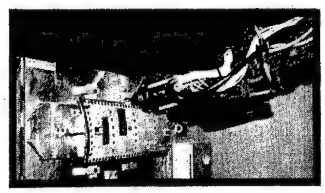
HIP DENSIFICATION OF CASTINGS

As indicated by the previous example of cast aluminum components, one of the major initiatives of the MT Program is to improve the integrity of castings and expand the utilization of casting technology for complex aircraft and engine components. A new approach termed Hot Isostatic Pressing (HIP) densification provides closure of microporosity and segregation commonly found in cast components, thereby increasing their integrity.

The program has enabled production of HIP densified castings. Cast properties have been improved up to 80 percent over wrought properties. For example, over 200,000 cast turbine blades have thus far been produced using this method. The HIP densification process has been incorporated as a new industrial base capability. Annual savings are estimated to be in excess of $1.5 million.

ROBOTIC SHEET METAL DRILLING

ROBOTIC SHEET METAL DRILLING & ROUTING



MANUFACTURING TECHNOLOGY PROBLEM
- Introduce Flexible Automation Into Aerospace Industry
- Reduce High Cost of Drilling and Routing

APPROACH
- Adapt Available Robot
- Establish and Validate a Robotic Station
- Implement a Shop Floor Robotic Cell

ACCOMPLISHMENTS & IMPACT
- F-16 Production Implementation
- 4:1 Productivity Increase
- Rework/Reject Rate Reduced From 10 Percent To 0
- Robotics Application Guide

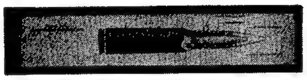
Under the ICAM Program, a robotic sheet metal drilling and routing cell has been successfully demonstrated on the F-16 production floor. In six months of operation, productivity has increased by 4:1 and perfectly worked parts have been the result. Six more robotic applications are being undertaken.

30mm ARMOR PIERCING ROUNDS

Depleted uranium (DU) plus ¾ weight percent titanium is used as a high density penetrator material to provide the armor piercing capability for the A-10 weapon systems. MT Program efforts established requirements for raw materials, methods for melting, casting, extrusion, swaging, forging, heat treating, and finishing. Material and process variables were correlated with ballistic performance to establish the most efficient and lowest cost methods to produce penetrators.

As a result, the U. S. capability to meet production requirements for DU plus ¾ weight percent titanium (now applicable to Army systems as well) was dramatically

30 mm ARMOR PIERCING ROUNDS



MANUFACTURING TECHNOLOGY PROBLEM

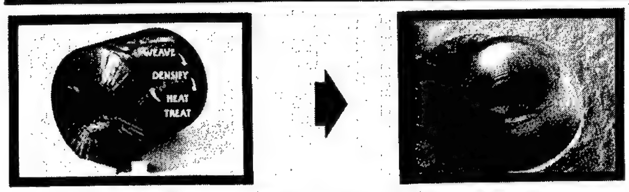
- REPRODUCIBLE METHODS FOR DU MASS PRODUCTION NOT ESTABLISHED E.G., CASTING, FORGING MACHINING
- HIGH COST OF EXISTING ROUNDS (~$12)

APPROACH

- ESTABLISH DU METAL SEQUENTIAL PRODUCTION METHODS FOR MELTING, CASTING, EXTRUSION, FORGING, MACHINING
- VALIDATE PRODUCTION PROCESS WITH BALLISTIC PERFORMANCE
- ESTABLISH PRODUCTION SPECIFICATIONS

ACCOMPLISHMENT & IMPACT

- MULTIPLE PRODUCTION SOURCES ESTABLISHED AT ~$5 PER PENETRATOR FOR A-10
- SIGNIFICANT COST AVOIDANCE (~$80M) VALIDATED
- ALTERNATE PROCESSES AVAILABLE FOR SURGE CAPABILITY AND OTHER DoD SYSTEMS



MANUFACTURING TECHNOLOGY PROBLEM

ESTABLISH RELIABLE PRODUCTION PROCESS FOR ONE PIECE THICK WALLED CYLINDERS

APPROACH

- HIGH & LOW PRESSURE AUTOCLAVE
- WOVEN, WOUND, & WRAPPED PREFORMS
- SCALE-UP NOSE TIP TECHNOLOGY

ACCOMPLISHMENTS & IMPACT

- PROCESS ESTABLISHED
- PROCESS VERIFIED BY ROCKET TESTS
- SPECIFICATIONS PREPARED
- INDUSTRIAL BASE AVAILABLE
- BASELINE FOR MX MISSILE

advanced and cost avoidance for the Air Force alone is estimated at $80 million.

AUTOSCAN METAL FLAW DETECTION

Autoscan is a newly developed process for detecting fatigue cracks in metal. Ultrasonics, similar to the radar detection of aircraft except on a microscopic scale, penetrates metal and pinpoints flaws, cracks, and defects. Autoscan provides a quality analysis of fastener holes aided by microprocessor control and signal processing.

In aircraft, fatigue cracks start at weak spots caused by fastener holes. Autoscan utilizes a focused ultrasonics beam with a small spot size which precisely scans the edges of a fastener hole and inputs all information to the microprocessor.

Approximately 15,000 fastener holes per year are inspected. Using conventional methods, the cost is $125 per hole and one hole requires approximately two hours. With Autoscan, the rate is 60 holes per hour, and the technique does not require potentially damaging fastener removal. As a result, the aircraft spends much less time in the depot, and the flight safety margin is greatly enhanced through more reliable inspection.

CARBON-CARBON MX NOZZLES

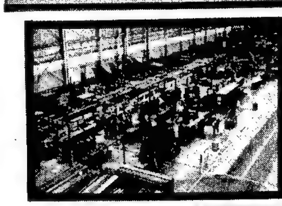
Carbon-carbon composites are the only materials that can withstand the 6500 degree F temperature and erosion conditions of MX rocket nozzles. Ballistic missile nose tips are made of this material, but are small compared to the billet sizes (400 pounds) needed for MX nozzles.

The manufacturing processes involved are high dollar value added steps applied to high dollar value preforms. Consequently, the rejection rate for billets must be low. The cyclic process requiring as many as seven cycles of densification and heat treatment is a major production cost.

A new MT Program high pressure process requires half the number of cycles as does the lowest pressure process. Excellent performance and erosion rates have been demonstrated. As there is no alternative to carbon-carbon nozzles, all propulsion stage contractors plan to use carbon-carbon one piece nozzles in the current MX full scale engineering development program.

F-16 MODERNIZATION

F-16 TECHNOLOGY MODERNIZATION PROGRAM



MANUFACTURING TECHNOLOGY PROBLEM

Outdated Facilities At AFP-4;
No Mechanism For Major Modernization

APPROACH

- ICAM Systems Analysis Techniques
- F-16 SPO Leadership and Commitment
- Design and Implement Selected Work Centers

ACCOMPLISHMENTS & IMPACT

- $25M A.F./$100M Contractor Investment
- 3 Work Centers To Be Implemented—Machining, Sheet Metal, Electrical Bench
- Contractor Commitment
- Benefits Tracking Methodology
- $25M Savings Through FY 79/ $370M Savings Projected

Production requirements for the F-16 have necessitated radical changes in production capability. Accordingly, the Air Force F-16 Systems Program Office (SPO) is investing $25 million to thoroughly evaluate the F-16 manufacturing capability.

The ICAM Program Office at the Materials Laboratory is managing all technical efforts for the SPO in this program. ICAM systems analysis expertise has been the driving factor in establishing the "top down" discipline required to investigate all facets of F-16 manufacturing and to identify the key cost drivers.

ICAM expertise in the application of computers to all aspects of F-16 manufacturing, as well as in modeling and simulation techniques, has established the direction for the design of work centers. Three work centers are being established to significantly improve production in machining, sheet metal fabrication, and electrical wire harness construction.

The F-16 contractor is investing $100 million to implement the new manufacturing procedures. A future savings of $350 million is projected from this process modernization effort.

Other Accomplishments

Additional significant Air Force MT Program accomplishments are as follows:

- Laser Drilling of Aircraft Engine Turbine Components
- ICAM Integration of Multiple Manufacturing Technologies
- Metal Fatigue in Aircraft Fasteners Decreased
- Computer Aided Ultrasonic Inspection Systems Integrated
- Computer Numerically Controlled (CNC) Contour Roll Forming
- ICAM Robotics/Sheet Metal Panels
- Integrated Blade Inspection System
- ICAM Program/Modules for Efficient Manufacturing Management and Operations
- Automated Assembly Fixture Drilling
- Production Process for F-16 Laminated Canopy
- Manufacturing Methods for Strategic Materials Reclamation
- Advanced Precision Machining

Incentives for Modernization

Calling for "innovative processes and approaches," the Air Force Aeronautical Systems Division (ASD) at Wright-Patterson Air Force Base announced in early June that future multiyear weapons contract awards will give incentives to contractors utilizing advanced manufacturing techniques such as those just described. The new policy, part of the division's overall MT Program, is a clear effort to cut costs and increase productivity among contractors. The policy serves as further proof of Air Force commitment to advanced manufacturing methods.

MT Objectives

Basically, there are three Air Force MT Program objectives:

(1) Establish manufacturing processes and validate them in a production environment.

(2) Establish a basis for the systems approach to manufacturing, including the integrated demonstration of computer based activities.

(3) Support production/manufacturing management activities throughout the acquisition life cycle.

It is intended that these goals satisfy the DoD and National needs and concur with an Air Force business strategy which seeks to incentivize greater industry involvement in MT transition and implementation.

To meet criteria for initiation, MT Programs for the Air Force must

- Provide solutions to broad based production problems.
- Establish a demonstrated production capability.
- Provide a needed manufacturing process which would not otherwise be available.
- Establish manufacturing processes which are beyond the normal risk of industry.
- Provide a tangible, worthwhile benefit or ROI.
- Be strongly linked to specific systems to be acquired.
- Have direct application to Air Force Depot needs.

These criteria, as influenced by the criticality of needs, are utilized by the Air Force in formulation, prioritization, and implementation of all MT Programs. The program requirements and budget requests are processed through various AF command levels. As an integral part of the MT Program operation and responsibility, close coordination and liaison is maintained with MT user organizations within the AFSC Acquisition Divisions, AFLC Logistics Centers, other Air Force laboratories, and industry.

MT Program Approach

The Manufacturing Technology Program provides the Air Force with the required advanced manufacturing technology to assure the producibility of future Air Force weapon systems and to establish the lowest cost methods for their manufacture, maintenance and retrofit. The MT Program is a vital mechanism for translating proven research and development advances into validated,

economic, certified production practices. It provides manufacturing processes and techniques in advance of acquisition requirements to

- Insure timely availability of materials, components, structures and devices.
- Alter outdated fabrication methods.
- Improve equipment and material utilization.
- Provide for alternate sources of critical/strategic materials and commodities.
- Reduce direct labor and labor associated overhead costs.

The Air Force MT Program encompasses a wide range of disciplines including manufacturing methods and production feasibility in the areas of metals, nonmetals, composites, and electronics and the development of computer integrated manufacturing procedures. One of the specific goals is the consideration of indirect as well as direct costs traditionally associated with manufacturing.

Definite Guidelines Established

All MT projects are conducted under contracts with private industry through competitive procurements. The contracts are negotiated with an Air Force business strategy aimed at securing all data rights, establishing commitments for competitive production sources and requiring end of contract briefings and demonstrations on contract results. These contractor briefings to government and industry competitors alike are a key factor in the transition of new or improved manufacturing technology to and within that industry segment.

The importance of early implementation of the newly evolved MT is being stressed through a tie-in with technology modernization initiatives—and by using implementation/technology transfer plans as a key factor in source selection. Technology transition is also achieved through technical workshops, seminars and disciplinary studies, in association with Industry and other Government agencies.

In summary, the MT Program

(1) Establishes new manufacturing methods and production procedures

(2) Implements technology transfer

(3) Stimulates the implementation of results and industry investment

(4) Directly supports small business and basic industry manufacturing efforts

(5) Builds on prior R&D results and demonstrations

(6) Impacts system acquisition and logistics areas where high ROI is possible.

The MT Program does not provide for

(1) Funding of capital equipment and facilities

(2) Conduction of R&D programs

(3) Support of proprietary developments.

Although the MT Program does initiate projects for new or improved manufacturing methods, a major effort is devoted to manufacturing cost reduction and production economics. The various individual MT Projects are justified and evaluated utilizing the following merit rating method:

RATING = (ROI) x (GENERIC RELEVANCE) x (PROBABILITY OF SUCCESS) x (PROBABILITY OF INCORPORATION)

The ROI factor is the ratio of the Real Production Cost Savings to the MT Program Investment.

Funding

The MT Program budget request is submitted to the Congress for review and approval as a P.E. 7.8011F line item. The approved FY-81 budget and proposed FY-82 funding are presented in Table I. The funding is divided into major application area categories which represent "focal point" planning areas within AFML. The Air Force MT Program budget has increased significantly in the past 7 years (i.e. from $12 million in FY-73 to $56.7 million in FY-80) due to the increased emphasis in acquisition and maintenance cost reduction, and technology utilization.

Attempts are being made to establish the use of 08M (3400) funds to better support AFLC needs and the use of 3600 funds to initiate a manufacturing R&D program.

MT Category	FY-81 Budget ($K)	FY-82 Proposed
Thermal Protection	0	0
Metal Structures	5,653	7,319
Composite Structures	3,200	6,250
NDE/QC	4,147	5,950
Propulsion	15,511	17,201
Fluids, Lubricants And Containment	0	750
Protective Coatings	0	400
Electronics	18,971	14,900
Hardened Structures	527	1,112
Munitions	3,238	3,977
Computer Integrated Manufacturing	18,600	19,900
TOTAL	69,847	77,759

Table 1

The Department of Commerce and Productivity

Highest Priorities Set

The Secretary of Commerce has identified the two highest priorities for the Department as international trade and productivity. To pursue these priorities, with the approval of President Carter, Secretary Klutznick in February of 1980 called for the establishment of the Office of Productivity, Technology, and Innovation (OPTI). This change set the organizational structure the Department will utilize to assume a major role in improving U. S. productivity performance.

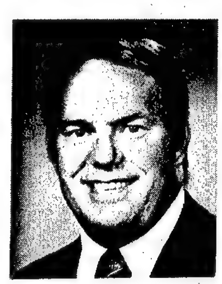
Headed by Assistant Secretary Jordan J. Baruch, OPTI absorbed the Office of Science and Technology that includes the National Bureau of Standards, the Patent and Trademark Office, and the National Technical Information Service. Beyond these efforts, however, OPTI has the primary responsibility for implementing the industrial innovation initiatives announced by the President in late 1979.

Technology Most Important Influence

The goal of OPTI is to increase the competitive position of U. S. industry. Improving productivity is one of the most effective means of achieving that goal. To improve productivity, the major emphasis will be on technology, which many agree is the most important influence on productivity. The primary target for this emphasis will be the private sector. The efforts of the Department should not be to supplant private sector efforts, but to play a supportive role in creating a climate to encourage industrial activities.

The strategy to achieve OPTI's goal will be threefold:

(1) To assist industry in improving productivity through the application of technology, science, and innovation



MR. CHARLES KIMZEY is Assistant Director, Cooperative Generic Technology Program, Office of Assistant Secretary of Commerce for Productivity, Technology and Innovation. Mr. Kimzey has been involved in the productivity field for over six years. His experience in productivity goes back to some of the earliest efforts of the Government to deal with the productivity issue. He was with the National Commission on Productivity and Work Quality chaired by Vice President Rockefeller. Mr. Kimzey was Director of the Capital and Technology Program for the Commission's successor agency, the National Center for Productivity and Quality of Working Life. His responsibilities in that capacity included the development of national policy recommendations to stimulate technology innovations as a means of improving U. S. productivity performance. He organized and conducted a Government/industry/labor delegation to examine the status of Japanese technology and manufacturing. He has private sector experience in his own retailing and service firm. He also organized and is currently a Director and Chairman of the Strategic Planning Committee of the Continental Bank and Trust Company of Springfield, Virginia. Mr. Kimzey has a Bachelor of Science degree from the University of Maryland and a Master of Business Administration degree from American University.

(2) To develop policies and programs to lower the barriers to productivity improvement

(3) To assist foreign buyers in purchasing U. S. goods and services.

For discussion purposes (risking great oversimplification), we can collapse the technological innovation process—for either product or process—into the following model:

1 TECHNOLOGICAL DEVELOPMENT/ COMMERCIALIZATION → 2 TECHNOLOGY TRANSFER → 3 IMPLEMENTATION

To impact national performance, implementation of technology by industry must take place. Great research and technology, if it doesn't find its way onto the plant floor, will be ineffective in achieving productivity and trade balance improvements. One way of attacking improved implementation is to effect improvements in the first two areas above. With this in mind, OPTI's programs are being developed to build in a "demand-pull" element on both the first two processes. This means that industry input will be sought to establish priorities (demand) for projects in technical development and transfer. An interest (or "market") should be evidenced by industry for these activities. To simulate ultimate implementation, OPTI's plans include both efforts to encourage the pace of technology development and to improve the transfer of technology.

Technological Development

Assistant Secretary Baruch has described one of the most important of OPTI's programs related to technological leadership and trade competitiveness. It is the Cooperative Generic Technology (COGENT) Program. This program will explore within the U. S. free enterprise system a principle the Japanese and the Germans have utilized very effectively—the principle of cooperation—industrial firms with one another and in turn with government. COGENT is an attempt to reduce the adversarial government/industry relationship as a means of accomplishing national goals. The specific objective of the program is to stimulate development and use of technology having application and usefulness in several industrial sectors. The target is generic technology which is downstream on the innovation spectrum from basic research, but considerably upstream from product development.

The principal advantages for a firm to participate in the program would be a leveraging of resources to accomplish tasks that are too large, too long term, or too risky for a single firm. This leveraging would be both financial and intellectual. Individual firms would pool their funds with the government to attack problems identified by industry. Firms participating would be afforded the opportunity to be involved with other firms in the process of identifying common problems and alternative solutions, as well as actively involved in achieving those solutions.

Nonprofit Corporation the Vehicle

The mechanism for cooperation is the Cooperative Generic Technology (COGENT) Center. The Center is planned to be a nonprofit corporation established by the private sector. Firms participating in the Center would elect their own Board of Directors. This private sector Board would allocate the resources of the Center.

The financial resources of the Center would come from both government and industry. COGENT will provide seed money to establish the Center, with support declining to 20% or less in the fifth year of operation. The industry contribution is considered a necessary ingredient for a Center as evidence of commitment to its success.

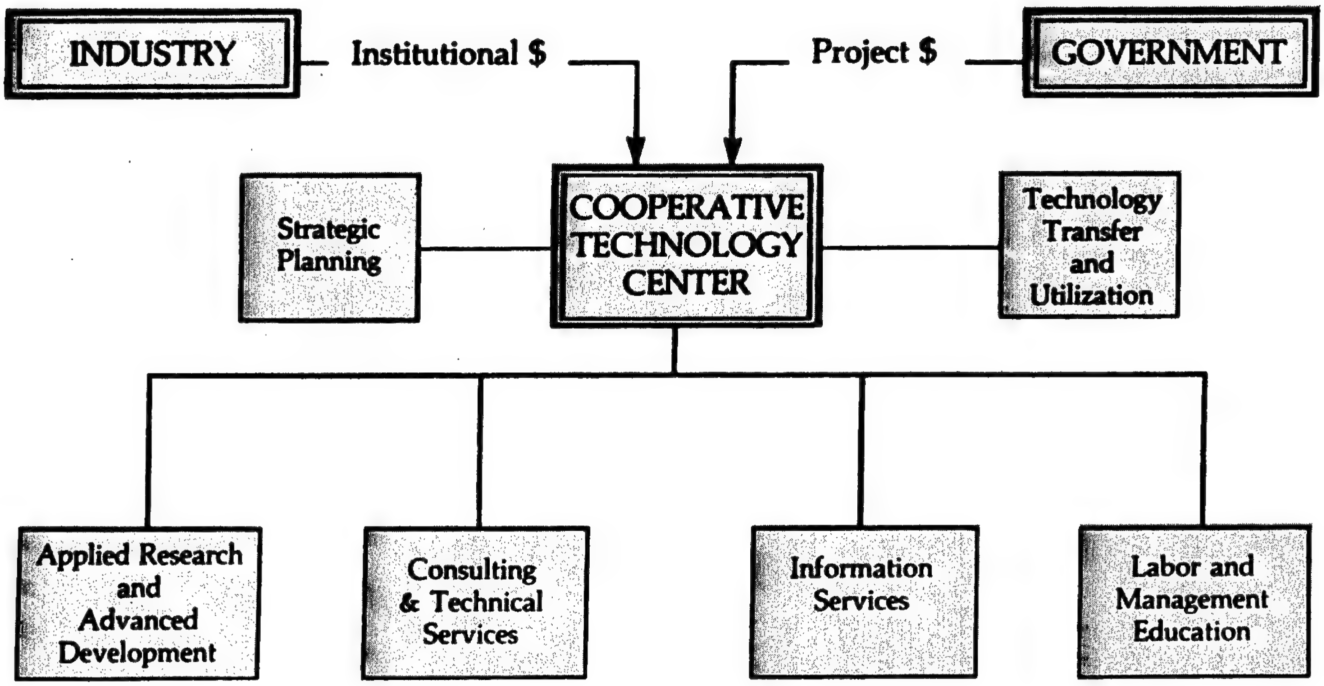
The activities of the Center are anticipated to include both technology development and transfer efforts. The joint research projects would be complemented by an information clearinghouse, technical services, and educational programs to train management and labor in the application of the technology produced.

Technical areas that are being explored for possible COGENT Centers include tribology (the science of friction and wear), computer integrated manufacture, welding, surface technology, and powder metallurgy. Studies seeking broad industry input performed by the staff of the COGENT Program have also supported the importance of these areas to the improvement of international competitiveness.

The COGENT Program is planned for fiscal year 1981 with funding currently indicated at $5.2 million. Public comment was solicited on the procedures for the program in June and July, 1980. The final COGENT Program procedures, taking comments received into account, were published in the Federal Register on August 14, 1980.

Commercialization

The process of commercializing a new product can cost between ten and one hundred times the amount spent for research to develop that product. These are painful facts, particularly to small business. OPTI intends to establish two Corporations for Innovation Development (CIDs) in FY 81 to address this problem. CIDs will provide direct



equity funding for the startup of firms wishing to develop and bring to market a promising, high risk innovation. CIDs will also provide assistance to potential applicants in obtaining second round financing and early management assistance to the firms funded.

One CID will be established in an industrial region, the other in a region less industrialized. A revolving loan fund provided by the Department of Commerce's Economic Development Administration will be established, with states expected to provide matching funds.

The CID program is being partly modeled after the successful British National Research and Development Corporation and existing state organizations such as the Connecticut Product Development Corporation.

Technology Transfer

The Federal government spent nearly $10 billion for research in 1978. The Center for the Utilization of Federal Technology (CUFT) is planned for FY 81 to generate a greater and more rapid return for the nation on the investment of Federal dollars in R&D. CUFT, to be housed at the National Technical Information Service (NTIS), will seek to increase the utilization by industry of federally developed technical information through intensive marketing including conferences, forums, and special services. CUFT will assemble and maintain a centralized information system on technology, will act as licensing agent for Federal patents, and will promote the interchange of professional staff between Federal laboratories and the private sector. CUFT will be the organization that industry can turn to when seeking information about federally developed technology. One very important element of CUFT will be development of a CUFT Technology Fellowship Program in which representatives of the private sector will be sponsored by their firms to spend equal time in Federal laboratories and in the private sector to assess potential yield of Federal technology to industry.

Domestic, Foreign Data Available

The Productivity Reference Service (PRS) is also planned for FY 81 to become the primary source of information in the Federal government on the subject of private sector productivity improvement. PRS will provide national and international information on such areas as capital, managerial know-how, and human resources. The PRS will focus on building the productivity information clearinghouse, which will include identifying and describing productivity success stories in the form of case studies and seminars.

A third initiative aimed at improving the transfer of technology planned for FY 81 is the Foreign Technology Utilization Program. This program, as part of the NTIS, will provide better access to foreign developments by collecting, translating, and disseminating selected scientific and technical information produced by other nations.

There is significant opportunity for the Department of Commerce/Office of Productivity, Technology and Innovation to learn from the long history of the Department of Defense in developing and encouraging implementation of new technology. Much of the work ManTech is supporting is directly related to the areas COGENT is exploring. As these program plans evolve, we are looking forward to identifying the ways and means our efforts can complement the Department of Defense as the common goal of productivity improvement is sought.

MTAG Coordinates Overall MT Effort

Steadily Moving Ahead

CHARLES P. DOWNER is Director of the Defense Industrial Research Support Office of the Deputy Under Secretary of Defense, Research and Engineering. He also serves as the Senior Staff Specialist for the Department of Defense Manufacturing Technology Program. Mr. Downer served for 25 years in the United States Air Force, where he specialized in production and procurement, industrial resources management, and manufacturing technology. Mr. Downer holds a B.S. degree from Mississippi State University.

Technology advances in manufacturing processes are a major goal of the Department of Defense. Although aimed at defense systems, technology improvements in the DoD manufacturing process normally have much wider application and can benefit civilian production as well. Such improvements are constantly emerging from DoD's Manufacturing Technology (MT) program.

For example, the manufacture and use of numerically controlled machine tools is a worldwide industry with far reaching implications across a broad segment of manufacturing and production processes. These tools are widely recognized as a vital part of modern mass production technology. First developed under an Air Force program to produce high performance military aircraft, they are just one of many spinoffs of the MT program.

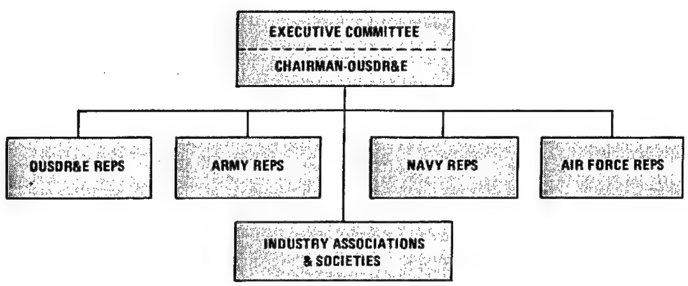
This MT effort is designed to develop or improve manufacturing techniques, processes, materials, and equipment in order to provide timely, reliable, and economical production of defense materiel. The program is proving to be not only a boon to military procurement budgets but important to the nation's entire economy.

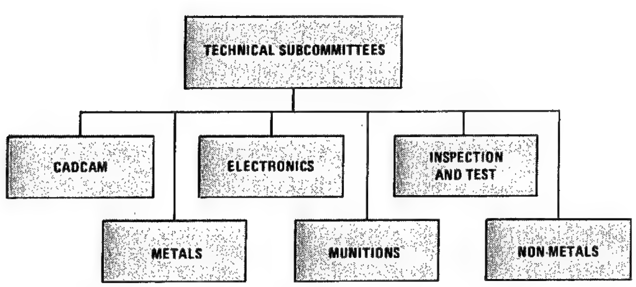
Service Interaction the Key

A key factor in the success of the MT program is close coordination and cooperation in program efforts between the services. Each service has a central MT office responsible for identifying, funding, and managing a servicewide program that addresses high cost manufacturing problems. To coordinate these efforts, DoD established the Manufacturing Technology Advisory Group (MTAG) composed of an executive committee and six technical subcommittees. This group reviews the planning implementation programs, and accomplishments of each MT office to identify duplication of effort, potential joint efforts, and technological voids in the overall MT effort.

Key elements in MTAG's mission are to

- Improve the responsiveness and efficiency of the U. S. production base by promoting technology diffusion and broad implementation of innovative manufacturing technology among the military services, industry, and other government agencies.
- Encourage the use of standard documentation formats among the services in their MT programs.
- Promote the reduction of weapon system costs and production lead times by encouraging the use of advanced technologies in U. S. industry.





Executive Committee Spawns Subcommittees

The MTAG Executive Committee includes two representatives of the Office of the Under Secretary of Defense Research and Engineering, one of whom is chairman, and two representatives from each military service. Meeting no less than four times a year,

this committee provides broad policy guidance and translates policy guidelines into specific goals and objectives. Their purpose is to promote integration of Army, Navy, and Air Force programs into a coherent, DoD wide MT program.

The Technical Subcommittees cover six subject areas: Metals, Nonmetals, Electronics, Computer Aided Design and Manufacture, Munitions, and Inspection and Test. Each subcommittee meets at least three times a year. Subcommittee members are nominated by the military service members of the Executive Committee. The subcommittees provide technical analysis, joint planning, and coordination on MT projects in their subject areas; identify areas of concern and possible duplication; and propose courses of action to alleviate inefficient manufacturing processes. Consider a few of the results of DoD's coordinated MT effort.

ICAM Program Far Reaching

An example of a large scale, long range MT program is Integrated Computer Aided Manufacturing (ICAM), an effort of broad national interest and increasing prominence. ICAM is a seven year, $100 million effort intended to increase manufacturing productivity and to lower defense systems costs through greater use of computers and computer technology in the aerospace industry. Although many individual elements of computer aided manufacturing—design, process control, production scheduling, material handling, and management information, for example—have been applied in industry, they have not been thoroughly integrated in a single system. The potential payoff of doing this is tremendous. Typical returns on investment for implementation of individual elements have been 30 to 50 percent. DoD believes that the integrated systems being developed under the ICAM program offer even greater potential for increasing manufacturing productivity and return on investment. It is expected that this DoD sponsored program, properly coordinated with industry and other government agencies, will act as a catalyst to focus national attention and action toward more rapid development and application of this emerging technology.

Net Shape Fabrication

Because of basic shortcomings in conventional forging processes, U. S. manufacturers spend more than $100 billion annually removing metal from parts where it is not needed. In the fabrication of many conventional forgings, as much as 90 percent of the starting material ends up as worthless chips. Through various MT efforts coordinated by MTAG, processes are being developed to fabricate parts to very near "net shape", so that little or no machining is required. In other words, we are learning to put metal where it is wanted in the first place rather than devoting energy to removing it from places where it is not wanted.

For example, the Air Force was primarily responsible for the development of diffusion bonding, which uses plate stock to produce near net shape parts. In diffusion bonding, two or more metal parts form a molecular bond under pressure. The parts are cut to near net shape, stacked as a sandwich similar to plywood, and subjected to a small pressure (much less than that needed for forging), thereby permitting the use of a smaller press.

Diffusion bonding is especially valuable for metals such as titanium and superalloys. It not only reduces metal removal costs, but also conserves critically short, expensive strategic materials. Much of the development work was applied to the B-1 bomber, whose design included more than 100 diffusion bonded parts; a few are illustrated in Figure 1. Although this aircraft did not reach production, the MT programs on diffusion bonding developed important processing techniques with wide applications for the manufacture of other products.

Casting Slashes Costs

Another MT project that has shown a very good return on investment involves a new process to manufacture a special "tank killer" armor penetrator made of depleted

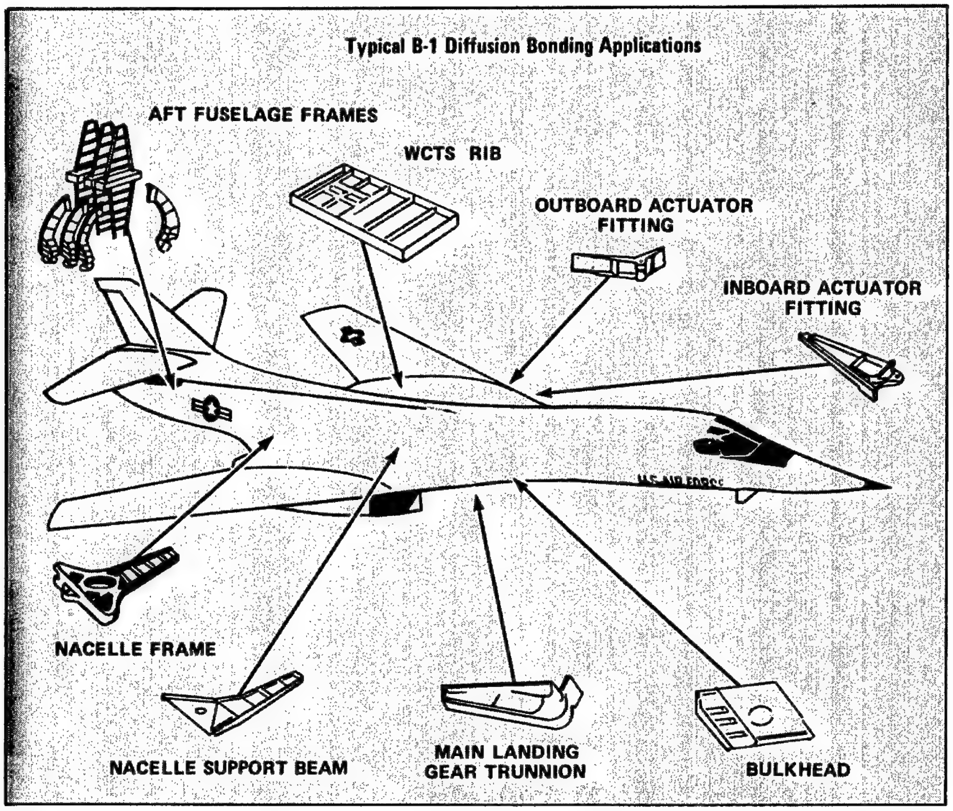


Figure 1

uranium. Development of this projectile was jointly sponsored by the Army and the Air Force for use in the GAU-8 gun. Originally, these penetrators were machined to the desired shape at a cost of $20 per unit. Then a new forging and swaging process was developed that reduced the cost to $8 per unit. Finally, cast penetrators were developed that reduce fabrication cost to an estimated $4 per unit.

These are just a few examples of the many successful MT programs that have been enhanced by MTAG coordination. Let's consider briefly the total scope of this program.

MT Concept

Begun in the early 1950's in the Air Force, DoD's MT program was given greatly increased emphasis in the early 1970's. DoD's appreciation of the program's contribution to reducing weapon systems manufacturing costs was recently summarized in a "Statement of Principles". The objectives of the program as outlined in the SOP are to

- Aid in insuring the economical production of qualitatively superior weapon systems on a timely basis.
- Insure that advanced manufacturing processes, techniques, and equipment are used to reduce DoD materiel acquisition costs.
- Continuously advance manufacturing technology to bridge the gap from R&D advances to full scale production.

- Foster greater use of computer technology in all elements of manufacturing.
- Assure that more effective industrial innovation is stimulated by reducing the cost and risk of advancing and applying new and improved manufacturing technology.

Geared To Cost Reduction

The primary purpose of this reemphasized and reoriented MT program is to reduce the manufacturing and life cycle costs of defense materiel. We all know that weapon systems costs continue to increase significantly, while the real dollars available for procurement diminish alarmingly. Defense procurement managers are constantly confronted with the need to reduce budgets and at the same time maintain or increase production. In view of this, weapon systems costs must be reduced if the United States is to maintain an adequate defense posture. Since manufacturing represents a major portion of these costs, the emphasis is placed on manufacturing cost reductions. The MT program is a primary approach to driving those costs down.

Broader Benefits

As already suggested, the potential benefits of the MT program go far beyond Department of Defense budgets. To see this, we only need to realize that manufacturing represents 30 percent of the gross national product—the largest single segment—and that DoD represents the largest single buyer of goods and services in the nation. Thus, reduction in DoD manufacturing costs will significantly impact a very large segment of the national economy and improve the competitive position of the United States in the world market place.

The development of numerically controlled tooling referred to at the start of this article is a classic example of what can happen with a large scale MT program. While it is not possible to accurately calculate the savings resulting from the original MT investment in that effort, it is safe to place it in billions of dollars.

Program Approach

The MT program is not an R&D effort. Rather, it is structured to bridge the gap between emerging R&D advances and full scale production. Projects are funded only after concept feasibility has been demonstrated. Currently, DoD is spending approximately $12 billion each year on R&D. An important goal of the MT program is to ensure that more of the results of this R&D investment are translated into fielded weapon systems.

The MT program provides proven options for the systems designer. A designer will not risk a new program by adopting new manufacturing methods or materials that are only laboratory curiosities. He wants proven manufacturing methods that are both production and service tested. With the proven options developed through MT efforts, productivity can be designed in and manufacturing costs can be reduced.

Potential benefits of manufacturing technology projects are threefold:

- Improved responsiveness of the industrial base
- Reduced systems costs
- Reduced dependence on foreign sources for strategic and critical materials by the development of domestically available substitutes.

For example, platinum cobalt for manufacture of traveling wave tubes used in electronic countermeasure equipment was once imported from the USSR. Then the Air Force produced a domestic material substitute through an MT project. The substitute

not only reduced cost and lead times, but increased the frequency range of the tubes, resulting in greatly improved ECM capability.

The 600 or so MT projects in operation at any one time encompass nearly all facets of DoD procurement and production. Typical examples of MT programs include the development of new welding techniques for tanks, advanced graphite and boron composites for missile and aircraft application, radiation hardened electronics, laser gyros, fiber optics, powder metallurgy forgings, and automated frame benders for ship beams.

Program Operation

Most DoD MT funds are placed on contract with industry as seed money to assist in establishing innovative production know-how. Such government assistance not only helps to lower defense systems costs, but also assists in the diffusion and application of new manufacturing technology throughout industry.

The results of MT projects are widely disseminated using several unique techniques. For example, each manufacturing technology contractor must perform an end of contract, full scale production process demonstration in his facility with industry competitors present. These demonstrations are particularly valuable since the majority of MT projects address generic manufacturing problems and the results have broad application.

Industry Cooperation

An important part of the MT program is close cooperation with industry. In addition to coordinating interservice programs, MTAG also seeks to engender greater service/industry coordination. Each year, MTAG conducts a coordination conference that serves as a means of technology transfer and diffusion. Industry is playing an increasingly important role in these meetings, which bring together their representatives and those of government agencies to stimulate awareness of proven manufacturing techniques and improve national productivity. Thus, every effort is being made to communicate manufacturing technology and avoid duplication of effort.

Realizing the urgent need to increase manufacturing productivity, industry has also endeavored to work closely with the manufacturing technology offices of each service to help reduce manufacturing costs. Representatives of industry actively participate in the structured process of identifying problems and establishing priorities for investment opportunities. Also, several industry associations participate in MTAG review and coordination of the entire program.

In cooperation with industry, the military services have held several "market analysis" seminars that resulted in detailed manufacturing cost analyses of major weapon systems. Subjects have included aircraft structures, composites, electronics, missiles, and tracked combat vehicles. Through such analyses, manufacturing problems and high cost elements in every major assembly, subassembly, component, and part of each major system have been identified. After identification of the cost drivers and manufacturing bottlenecks, manufacturing technology projects have been developed and prioritized to those areas of greatest need and greatest payoff.

MTAG Producing the Goods

In summary, the capability to produce cost effective, qualitatively superior weapon systems on a timely basis is significantly affected by the availability of advanced manufacturing technology. The DoD MT program, carefully coordinated by MTAG, has demonstrated that it can provide that technology. In a report released to Congress, the Comptroller General of the United States recently stated, "GAO believes that in order to remain internationally competitive and to maintain a strong industrial base, actions must be initiated to make manufacturing productivity a national priority." This is what the MT program is all about.

A Look At Electronics in 5-10 Years

CAD/CAM Subcommittee Pushes ECAM

Frederick Michel, Chairman

The CAD/CAM Subcommittee again had an active year. It currently has 40 members representing the three services, a DoD function, two other government departments, and five industry associations.

One of the more active groups was the ECAM (Electronics Computer Assisted Manufacturing) Ad Hoc Group chaired by Fred Michel. The ECAM project was recommended by the Electronics Industry Association at MTAG '78. The group is initiating the first steps in planning and executing a computer integrated electronics manufacturing program for DoD. It has the objective to develop a top down view or architecture of the techniques, processes, and management controls used in the design and manufacture of military electronic equipment and to identify the opportunities for automation and computer integration.

Upgrading Quality, Downgrading Cost

Interest in CAD/CAM electronics has been motivated by an awareness that approximately 33 percent of the cost of aircraft and 60 percent of the cost of missiles is for electronic components. This percentage is increasing because of increased performance requirements and the complexity of future systems.

Hybrid circuits are the third ranking cost driver in electronic circuits. The absolute cost of hybrids is also rising, as is their relative cost when compared to other DoD electronic components because of the lack of a need for hybrid circuits in the commercial marketplace.

Specifically, the Group's objectives are

- To study the feasibility of a tri-service electronics wedge
- To develop a tri-service electronics wedge promoted by both the CAD/CAM and Electronics Subcommittees of MTAG.

Representatives of the CAD/CAM and Electronics Subcommittees met in July 1979, summary letters of that meeting were written to the MTAG Executive Committee, and representatives of the Group met in January 1980 at Wright-Patterson Air Force Base to write a charter and discuss specific plans. Group representatives are currently identifying specific areas and relative tasks that can be applied to the whole project.

Opportunities for Automation

The CAD/CAM Electronics Ad Hoc Group works closely with the CAD/CAM Subcommittee. The Ad Hoc Group was established to interface with industry associations and with the CAD/CAM Subcommittee. It intends to develop a contacts effort with industry to augment the use of computer aided design and computer aided manufacturing in the production of electronic circuits and equipment. Like the MTAG Electronics Subcommittee, it will study the development of techniques, processes, and management techniques necessary for the design and manufacture of highly sophisticated electronic equipment.

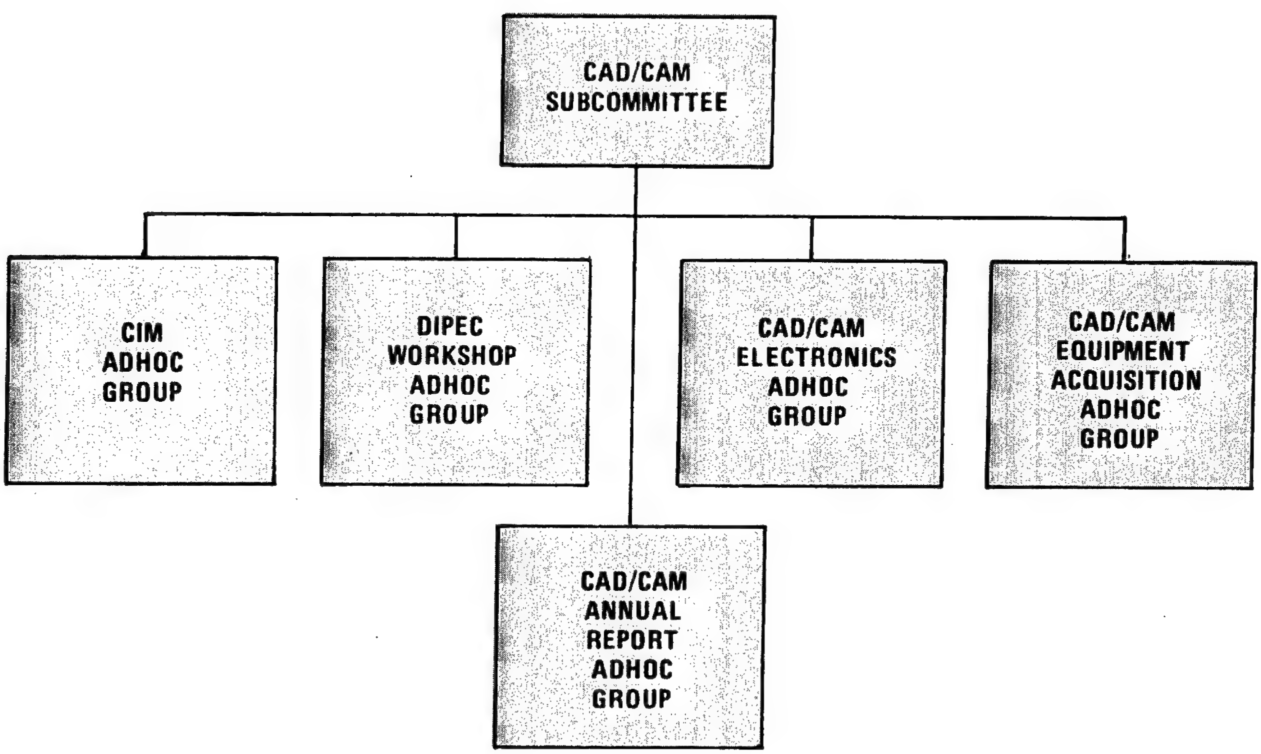
Thus far, the Group has identified a top down view or architecture as its first priority of action. A U. S. Army MICOM representative has been designated project manager for a contract to develop the first stage of this technology. In the near future, it is anticipated that Air Force and Navy representatives will be brought into the program as participants in the basic contract or to pursue specific designated areas.

Chairmanship Transferred

The full committee held two meetings—one on April 30, May 1 at Hartford, CN. At that meeting, the members discussed the FY 81 CAD/CAM programs of the three services, established Ad Hoc committees and discussed ongoing and potential tri-service projects. The transfer of the chairmanship from Dennis E. Wisnosky to Frederick J. Michel was one of the major events. Dennis has taken a job with International Harvester, where he hopes to apply the good things he has been instrumental in developing with the Air Force ICAM program. We all wish him the best of luck.

The other meeting was held on August 14 and 15 at St. Louis, MO. The discussions at this meeting centered around the Ad Hoc group activities, the ICAM Architecture, the DIPEC/NC Workshop, and MTAG '80.

CAD/CAM SUBCOMMITTEE



Coincident Meetings With Societies

Electronics Subcommittee Features Generic Organization

Charles E. McBurney, Chairman

The major accomplishment of the Electronics Subcommittee is the effective coordination of the three services' MT programs in electronics and optics. As a result of continuing coordination efforts by program managers and engineers, a number of projects have been dropped or deferred and a larger number have been or are being run jointly to conserve funds.

The Electronics Subcommittee serves as a forum for exchange of technical information and ideas and stimulates the use of advanced technology in new areas. It deals with the many processes used to produce electronic and optical products; these are so varied that the group concentrates mostly on technologies that are common among the services. In this way, the Subcommittee can influence the individual service's programs in a constructive manner.

Proven to be A Dynamic Force

Several Subcommittee activities are used in the exchange of information and promotion of effective use of MT funds.

- Proposed projects are coordinated by Subcommittee members to eliminate potential duplication.
- Workshops and conferences are sponsored to create dialogue between DoD, industry, and academia concerning program direction and future projects.
- Program data is presented at the Annual Meeting to stimulate discussion concerning trends occurring in the service's programs.

Subcommittee activities for the year are set during the annual coordination meeting of the full Subcommittee membership. There, each service's budget and five year plans are reviewed; common areas of interest are identified and coordination actions are recommended to the services. After the actions have taken place, the results are documented in the Electronics Subcommittee Annual Report, which is available to both government and industry.

The Subcommittee has shown itself to be a dynamic force. During its six years of operation, it has been responsible for eliminating a number of projects that would have duplicated previous work, encouraged several joint service projects, and hosted a number of workshops and conferences. The results of these activities reflect the effective support of the Subcommittee members.

Six Technical Working Groups Utilized

The activities of the Electronics Subcommittee are carried out through six technical Working Groups in addition to those performed by the full Subcommittee. Technical Working Groups establish rapport with industry associations having parallel interests. The **Hybrids Circuit Working Group**, for example, holds its annual planning conference immediately before or after the

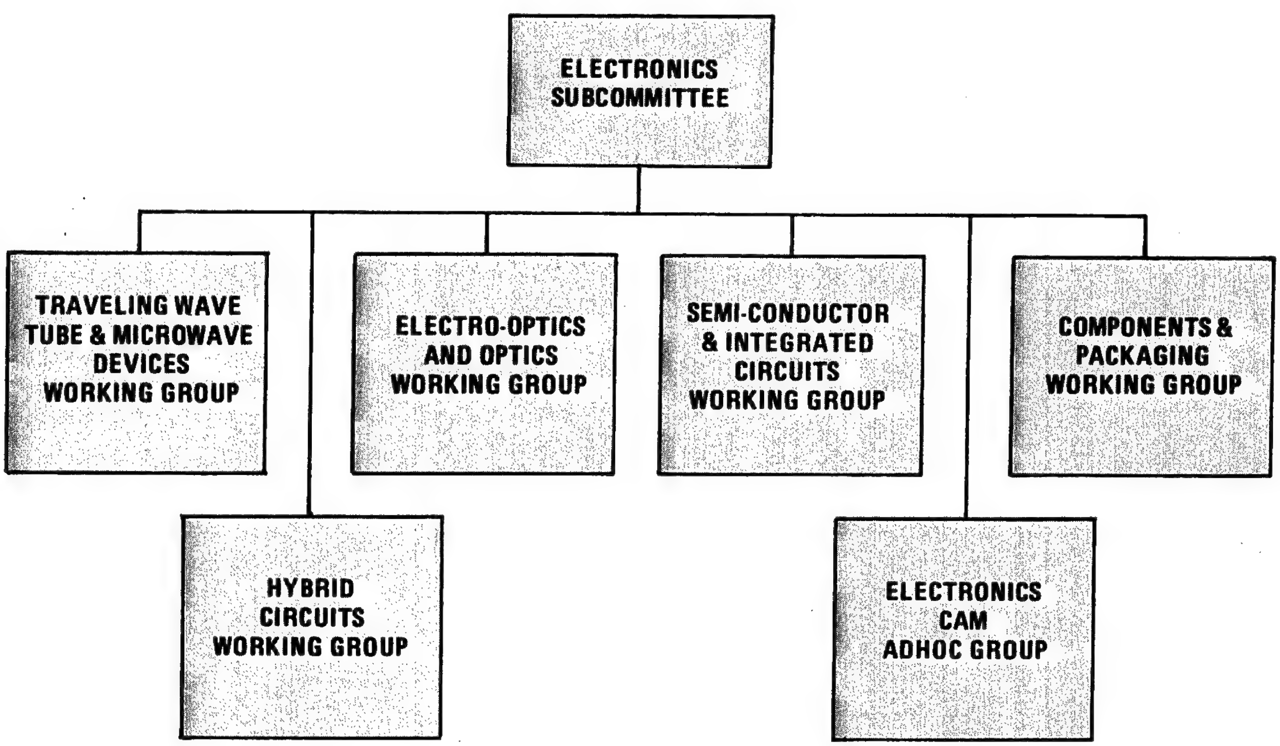
International Hybrids Society's Annual Meeting and discusses work of particular interest to the military. The **Components and Packaging Working Group** held its First Annual Planning Meeting at the same location and time as the International Packaging Conference. This back to back scheduling allows the same persons to attend both meetings and use civilian input to serve military needs. Also, there is little additional travel expense and time expended away from the office.

For the first time this year the **Traveling Wave Tube and Microwave Device Group** held its workshop following the Power Tube Conference at Monterey, California. And the **Electro-Optics Working Group** held its First Planning Meeting at the Night Visions Labs where much of its work is initiated and sponsored, while the **Semiconductor and Integrated Circuits Group** found it expedient to hold its sessions immediately after meetings of the Very High Speed Integrated Circuits (VHSIC) Steering Committee. While the **Electronics CAD/CAM Interface Group** has not yet held a formal technology planning conference, it is expected to be back to back with an Integrated Computer Aided Manufacturing (ICAM) meeting.

Changing Defense Requirements Play Role

The events that transpire during these Planning Conferences vary with the needs of the groups, but generally include an assessment of what new technologies are available and what new needs have surfaced as a result of changing defense requirements. By bringing together Tri-Service specialists and experts from the Electronic Industries Association and leading industrial firms, many short range problems can be solved immediately and solutions to long range problems worked out later. Plans and roadmaps are assembled or updated to show recent research and development progress, upcoming Manufacturing Technology efforts, and projected end item procurement schedules. The three—R&D, MT, and end items—must mesh together in a timely manner to be fully effective. Results to date have exemplified the practicality of this approach.

ELECTRONICS SUBCOMMITTEE



Triple Activity Format

Metals Subcommittee Provides Focal Point

Gordon B. Ney, Chairman

The Metals Subcommittee has proven to be an aggressive and dynamic force. During its six years of tenure, the Subcommittee has been responsible for eliminating six projects which would have duplicated previous work, forming fourteen multiservice projects, and hosting six workshops and seminars. These accomplishments reflect the hard work and cooperative spirit of the Subcommittee members.

Common Technologies Center Stage

We see our objective as providing a forum for the exchanging of technical information and ideas and maximizing the use of advanced manufacturing technology. We are attempting to prevent duplication, promote joint efforts where appropriate, and stimulate the application of advanced manufacturing technology to problem areas not previously considered. We deal with all processes required to produce metal and structural ceramic products, but concentrate on those technologies that are common, or—in our opinion—should be common, among the services. Concentrating on these technologies enables us to favorably influence the individual service programs in a way that each service, working by themselves, cannot.

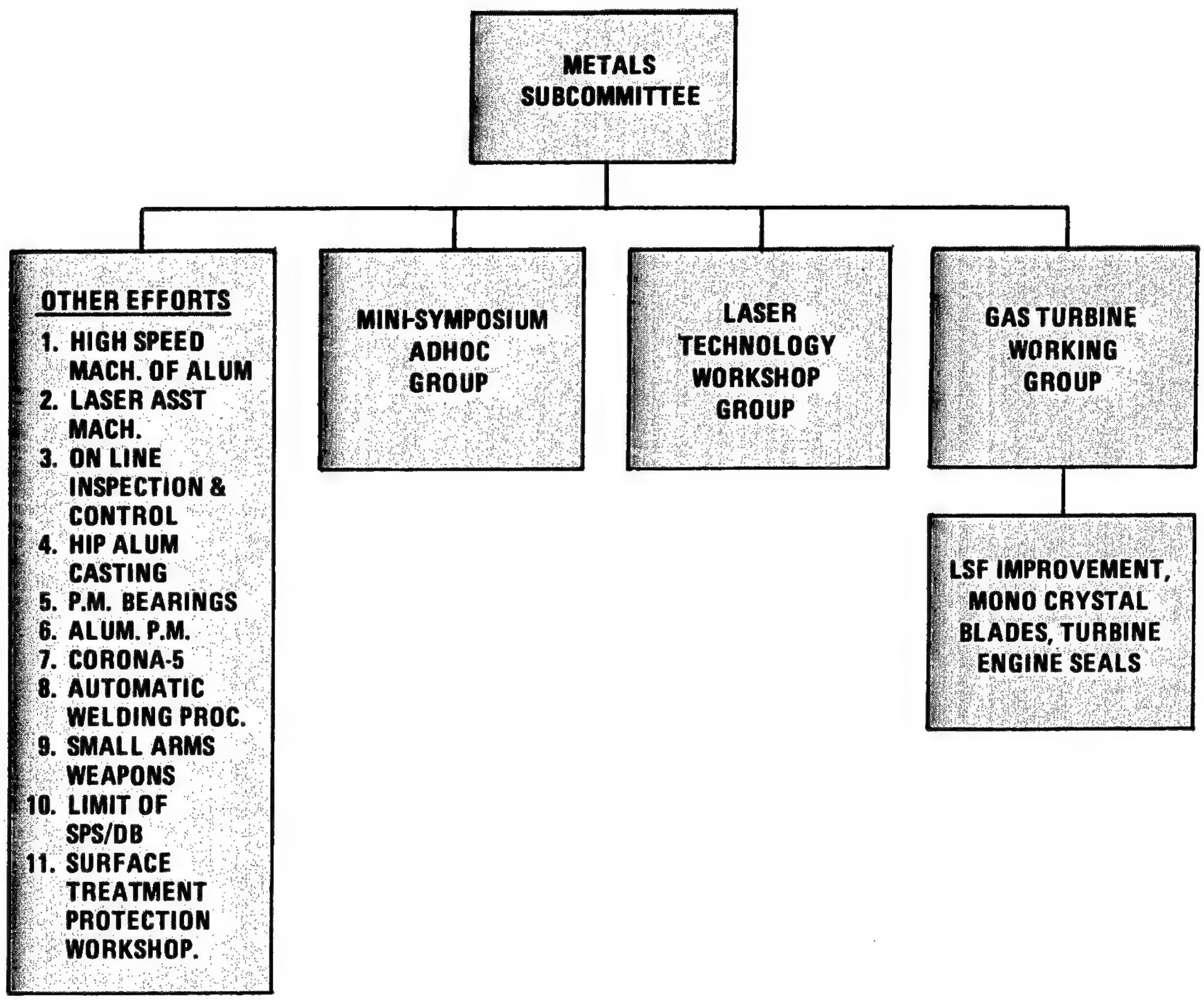
Three types of activities have evolved in accomplishing our objectives:

- Individual projects are reviewed to eliminate potential duplication of effort.
- Program data is analyzed and presented at the Annual MTAG Meeting to stimulate discussion concerning the trends occurring in the Services' programs.
- Workshops and seminars are sponsored to create a dialogue between DoD and Industry concerning program accomplishments and future directions.

Actions Assigned to Service Reps

We establish our activities for a given year through a process that begins with a Subcommittee meeting in late summer each year. At this meeting, the Services' budget, apportionment, and five year program plans are reviewed. Common areas of interest are identified and appropriate actions concerning them are recommended to the MTAG Executive Committee. Once approved, the actions are assigned to service representatives for execution. The results then are documented annually in the Metals Subcommittee report.

METALS SUBCOMMITTEE



Two Major Thrusts Considered

Non-Metals Subcommittee Takes Early Look

Robert C. Tomashot, Chairman

Membership of the Non-Metals Subcommittee is arranged so as to provide broad coverage of the Tri-Service Manufacturing Technology Program that involves both structural and nonstructural nonmetallic materials and the processes for their effective use in weapon systems. AMMRC and the aviation and missile commands of the Army; NAVSEA, NAVAIR, NAVORD, and NAVMIRO of the Navy; and AFWAL/ML and AFLC of the Air Force have provided continual technical specialists to the Subcommittee. Also, liaison members from NASA and DoE recently have been added.

Planning Two Years Ahead

From a program planning standpoint, the most beneficial results of Tri-Service coordination occurs on the FY +2 program. Thus, the usual mode of operation is to hold a summer meeting of the Subcommittee for a detailed review and examination of each Non-Metals ManTech project in its earliest stages of documentation. For example, in July of this year, the planned programs for FY 82 were reviewed by the Subcommittee for the purpose of eliminating any duplication of effort, suggesting improvements to the project, or establishing possible

joint or cooperative projects. After this type of review, written summary descriptions of the projects are furnished to the pertinent industry associations for their review, and a followup coordination meeting is held with industry association members for suggestions and comment. Other Subcommittee meetings are held during the year to review the status of ongoing projects. Periodically, major Tri-Service reviews of projects concerning non-metals manufacturing are held to completely update industry on the status and results of contractual programs. In addition, workshops are held on selected subjects such as the one on "In-Process Quality Control of Composite Materials/Fabrication" held in April 1980.

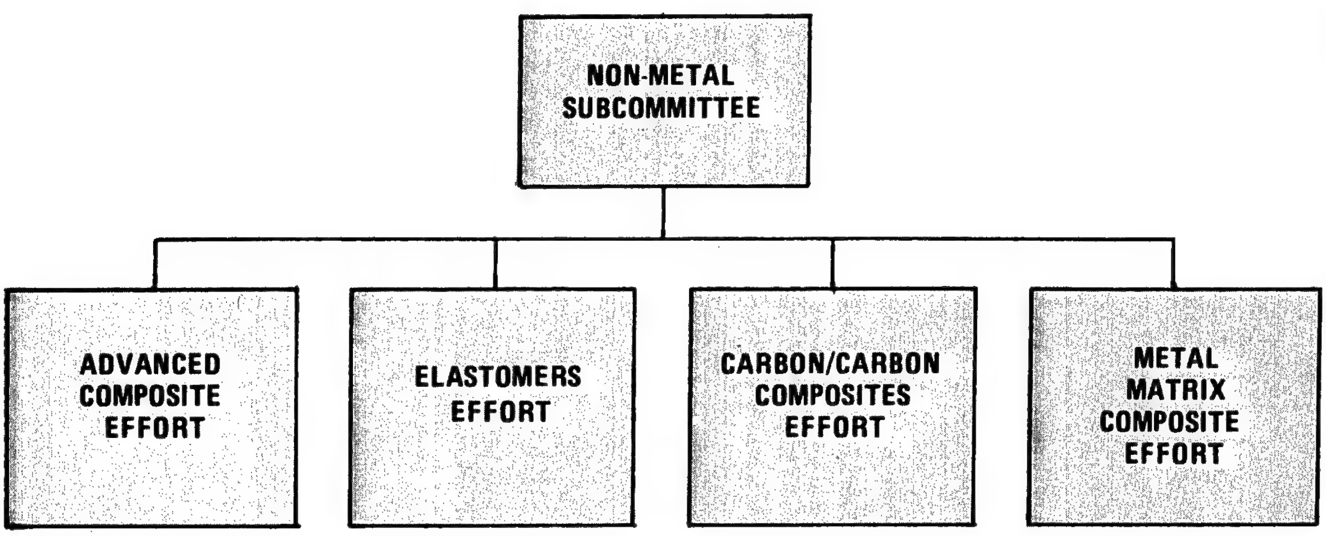
Cooperative Programs Result

Two of the major thrust areas to meet non-metals manufacturing requirements are structural composites fabrication and carbon-carbon materials processing.

- Structural composites application in aircraft and helicopter systems is continually expanding and manufacturing improvement goals common to all three services have led to several jointly funded, cooperative programs.
- The need for precisely manufactured carbon-carbon materials in missile reentry nosetips and rocket nozzle throats is also common to the three services and has resulted in cooperative programs to work selected areas of the total technology required.

It is expected that these areas will continue to be major thrust and interest areas to the three services and the Subcommittee. Industry comments and suggestions on programs to improve manufacturing technology in these areas as well as on any other subjects are welcome and can be submitted to the respective service contacts.

NON-METAL SUBCOMMITTEE



CY 1980

Anticipating Production Problems

Test & Inspection Subcommittee Improving Quality

Edward Criscuolo, Chairman

A preponderance of nondestructive testing projects over the past three years, especially in the intensely funded metals field, may reflect the trend in those areas of manufacturing technology covered by the Test and Inspection Subcommittee of MTAG. Potential tri-service programs in neutron radiography, automatic infrared inspection, and automatic ultrasonic inspection also are significant. The scope of the T&I responsibility covers a wide spectrum, including (besides the aforementioned) dimensional measurement via noncontact methods, composites with their complex characteristics, the dynamic demands of the electronics industry, munitions manufacturing that is sensitive to safety and reliability features, and increased use of computer aided inspection to improve on human interpretation. An increase in funding of 50% over the previous year has signalled what is ahead in this area of MTAG activity.

Large Technical Audience Served

The objectives of the Test and Inspection Subcommittee are as follows:

- To provide technical assessment and tri-service coordination of specific proposed manufacturing technology projects in the area of test and inspection. Through the examination of projects a determination is made for compatibility with DoD objectives, duplication of effort, and potential for joint funding.
- To provide an industry-government forum for the discussion of anticipated production problems and the identification of potential solutions and to assess the impact of privately sponsored work on the areas of interest.
- To make recommendations regarding joint service efforts, elimination of duplication, and establishment of broad DoD manufacturing technology goals in Test and Inspection.

Special Groups Provide Interface

The Subcommittee interfaces with each of the other subcommittees and therefore has been subdivided as shown in the accompanying chart. Four meetings were scheduled for 1980:

April 15-16	NAVMIRO Philadelphia, PA	Review plans for Minisymposium
July 29-31	NSWC Silver Spring, MD	1st Review of 1982 Submission
August 26-28	AMMRC Watertown, MA	2nd Review of 1982 Submission

September 10	NSWC Silver Spring, MD	MTAG XII Report
October 19-23	MTAG XII	Annual Meeting

Reviews Identify, Coordinate

A Review of the 1982 proposed projects served the purpose of:

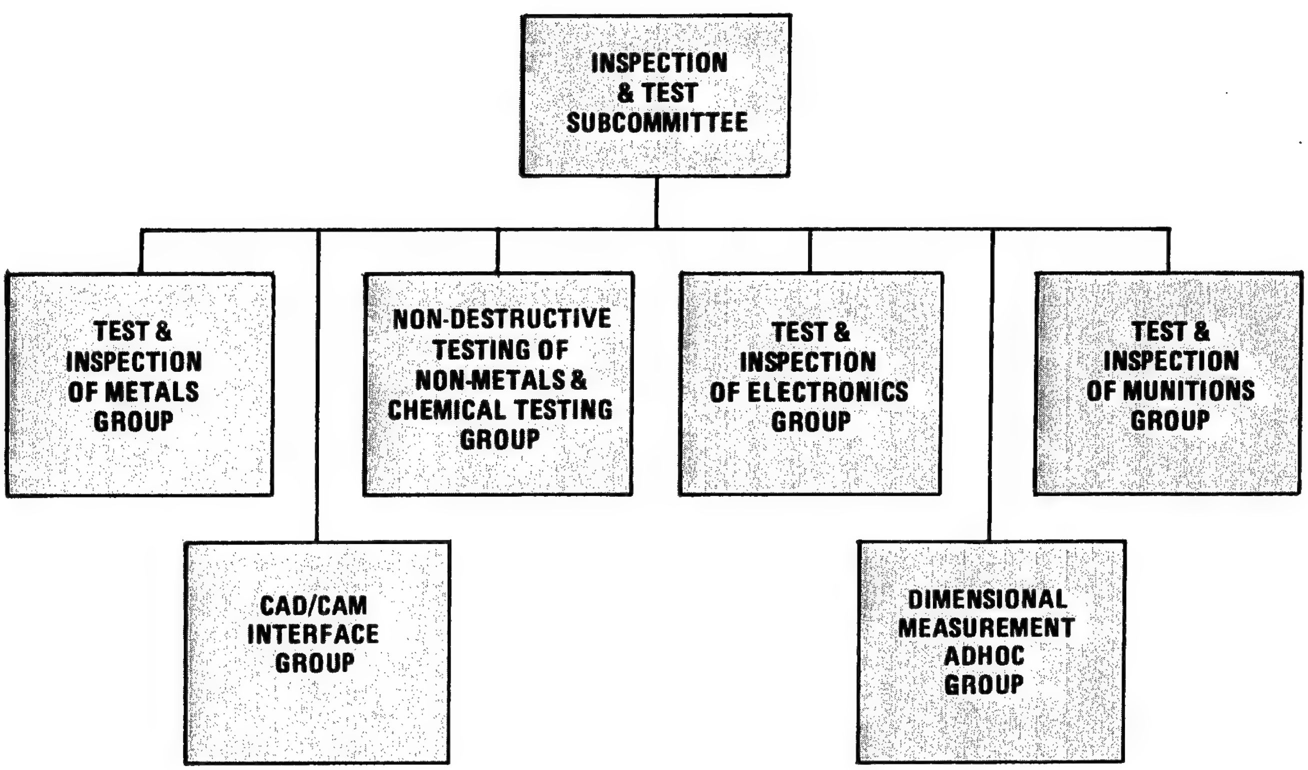
- Identifying potential duplication of proposed projects.
- Identifying overlaps where coordination of projects will be useful (joint programs).
- Identifying persisting Test and Inspection problems.
- Coordinating service efforts with those of industry.

Minisymposium to Feature Ten Titles

The Subcommittee has organized the following subjects for the Minisymposium of the 1980 Annual Conference:

— Eddy Current Surface Inspection of Discs
— Integrated Blade Inspection System (IBIS)
— In-Service Inspection System (ISIS)
— Mobile Neutron Radiography System
— Cannon Barrel Inspection
— Automatic Inspection Device for Explosive Charge in Shell (AIDECS)
— Gas Bearing Gyro Inspection System
— Angular Visual Security Test Set
— High Energy Real Time Radiography
— Detection of Cracks Under Fasteners

INSPECTION & TEST SUBCOMMITTEE



Commercial Impact Pronounced

Munitions Subcommittee Handles Full Spectrum

John Kaschak, Chairman

The MTAG Munitions Subcommittee is concerned with the full spectrum of triservice munitions manufacture. In achieving its multifaceted goals, the Subcommittee maintains close liaison with industry and other supportive areas of manufacturing technology. Subcommittee membership spans the three services, resulting in an unusually broad range of munitions expertise being applied to MT projects.

The primary responsibilities of the Munitions Subcommittee are to

- Assess and coordinate proposed MT projects for compatibility with DoD MT Program objectives, duplication of effort, and joint funding.
- Identify and propose solutions to anticipated production problems.
- Recommend areas of implementation and provide technology transfer for completed projects.
- Maintain knowledge of current state of the art production practices.
- Interact with industry to foster it as a useful resource for program planning, coordination, and implementation.

MM&T Projects Demonstrated

The Subcommittee has been involved with many varied projects to date. One area of popular interest has been the FAE II Die Casting and Skin Roll Forming MM&T Program. FAE II is an acronym for Fuel Air Explosive, 2nd generation, which is composed of two sizes of bombs—a 500 lb (BLU-95/B) and a 2000 lb (BLU-96/B). The FAE II MM&T Program is being developed on a triservice basis so that a potential $58M cost savings can be realized in production.

Basically, the FAE II Program is directed at two BLU-96/B high cost areas: the tailcone die casting die and the skin roll forming machine. The tailcone die is intended to replace the present sand mold casting techniques with a die casting die that is the most cost effective method of production. Die castings typically weigh 10 pounds or less, but as much as 50 pounds on rare occasion. In contrast, the BLU-96/B tailcone casting will weigh an estimated 72 pounds and will be the largest known die casting ever produced. The effort represents a significant advancement in die casting technology, with the die being about 21 feet high and weighing in excess of 60 tons. The technology demonstrates a capability of die casting large surface areas (12 square feet) of high strength (16,000 lb tensile) components.

In addition, a two roll form machine is being developed to roll form premachined, ten foot long aluminum sheets into BLU-96/B warhead fuel container skins. The machine is the largest two roll machine ever built—sixteen feet long, thirteen feet deep, and five feet high. The two roll form machine is much more cost effective than three roll machines because protective coatings are not damaged,

additional forming required by three roll machines is eliminated, and all secondary machining is eliminated since a premachined sheet can be used.

Planning Meetings Held

The activities of the Munitions Subcommittee were structured around three General Meetings and two tech demos in 1980 as follows:

(1) General Meeting, "Focusing the CY80 Program," ARRADCOM, Dover, N.J.;

(2) General Meeting, Review of "Tri-Service FY-81/82 MMT Program", "Formulation of Conference Technology," ARRADCOM, Dover, N.J.;

(3) General Meeting, "Dry Run Annual Conference Presentations," ARRADCOM, Dover, N.J.;

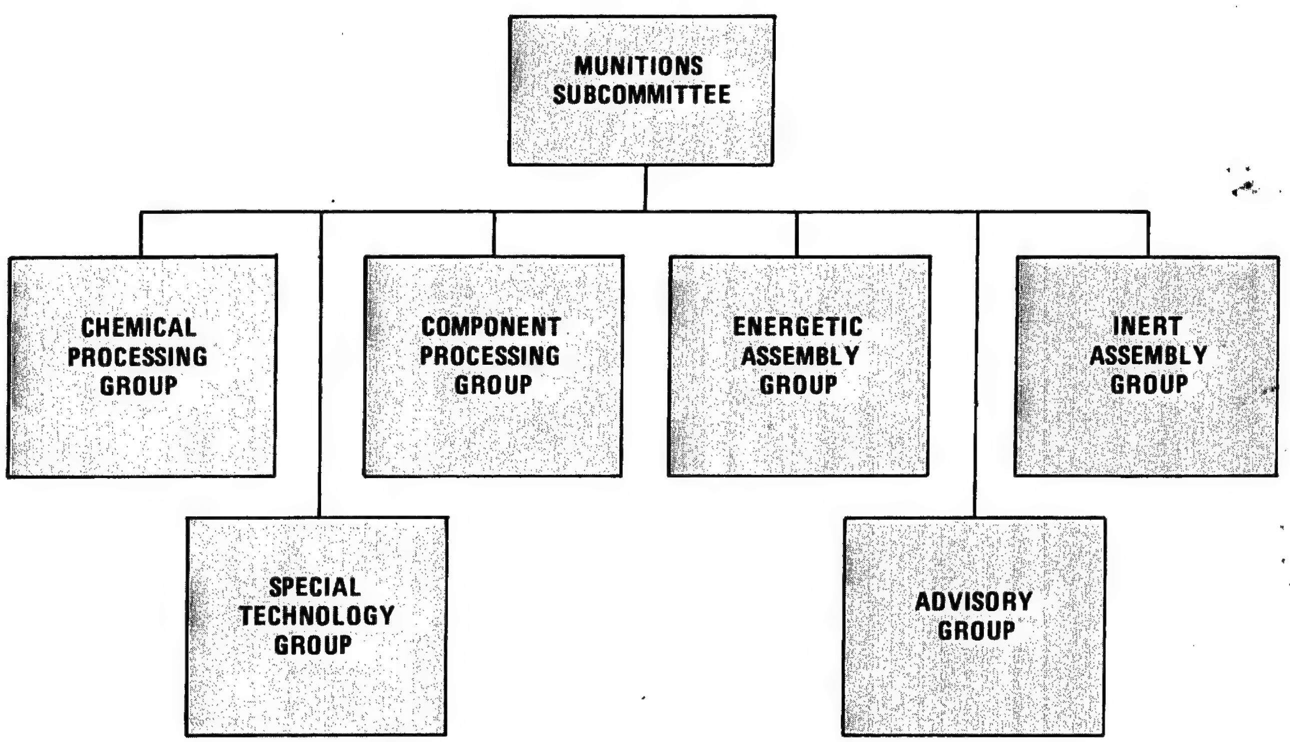
(4) Tech Demo during (1) above: "Continuous Melt-Pour Controlled Cooling Prototype Facility";

(5) Tech Demo during (2) above: "Drying of Low Density Ball Propellant".

MTAG MUNITIONS SUBCOMMITTEE		
CY80 MM&T Project Demonstrations		
Date	Project Title/Location	MPBMA Point of Contact*
Feb – Completed Dec – Next Demo	Auto Production Equipment for Assembly of M692 Adam Mine/Louisiana AAP	Mike Pino Ext 6786
May – Completed	Continuous Propellant Drying, Salt Coating & Glazing/Badger AAP	Ted Gropler Ext 2823
May – Completed	Smoke Mix Facility (GLATT – Colored/CS)/Pine Bluff Arsenal	Wally Ng Ext 6791
June – Oct (In Production)	Separation of Fine Explosives From Spent Acid and/or Water Slurries/Holston AAP	Wally Newcomb Ext 6751
June – Dec (In Process)	Ball Propellant Pilot Plant Studies/Badger AAP	Ted Gropler Ext 2823
September	90 ppm Continuous Motion M42/M46 Grenade/Fuze Assembly Machine/Kansas AAP	Matt Condit Ext 6786
Sep/Oct	One Piece Skin Rolling Machine – FAE II/Kurt Mfg, Minneapolis, MN	Ed Cassidy Ext 4081
Sep/Oct	Production Technique for Improved WP 155mm XM825/ARRADCOM, Edgewood Arsenal, MD	Wally Ng Ext 6791
October	Acceptance of Single Base Propellant Made by the Continuous Automated Process/Radford AAP	Ted Gropler Ext 2823
Oct/Nov	Equipment to Lap Center Core Propellant Charges/Crane AAP	Dick Koppenaal Ext 6791
November	Drying of Low Density Ball Propellant/ARRADCOM, Dover, NJ	Ted Gropler Ext 2823

* AUTOVON 880-XXXX
Commercial (201) 328-XXXX

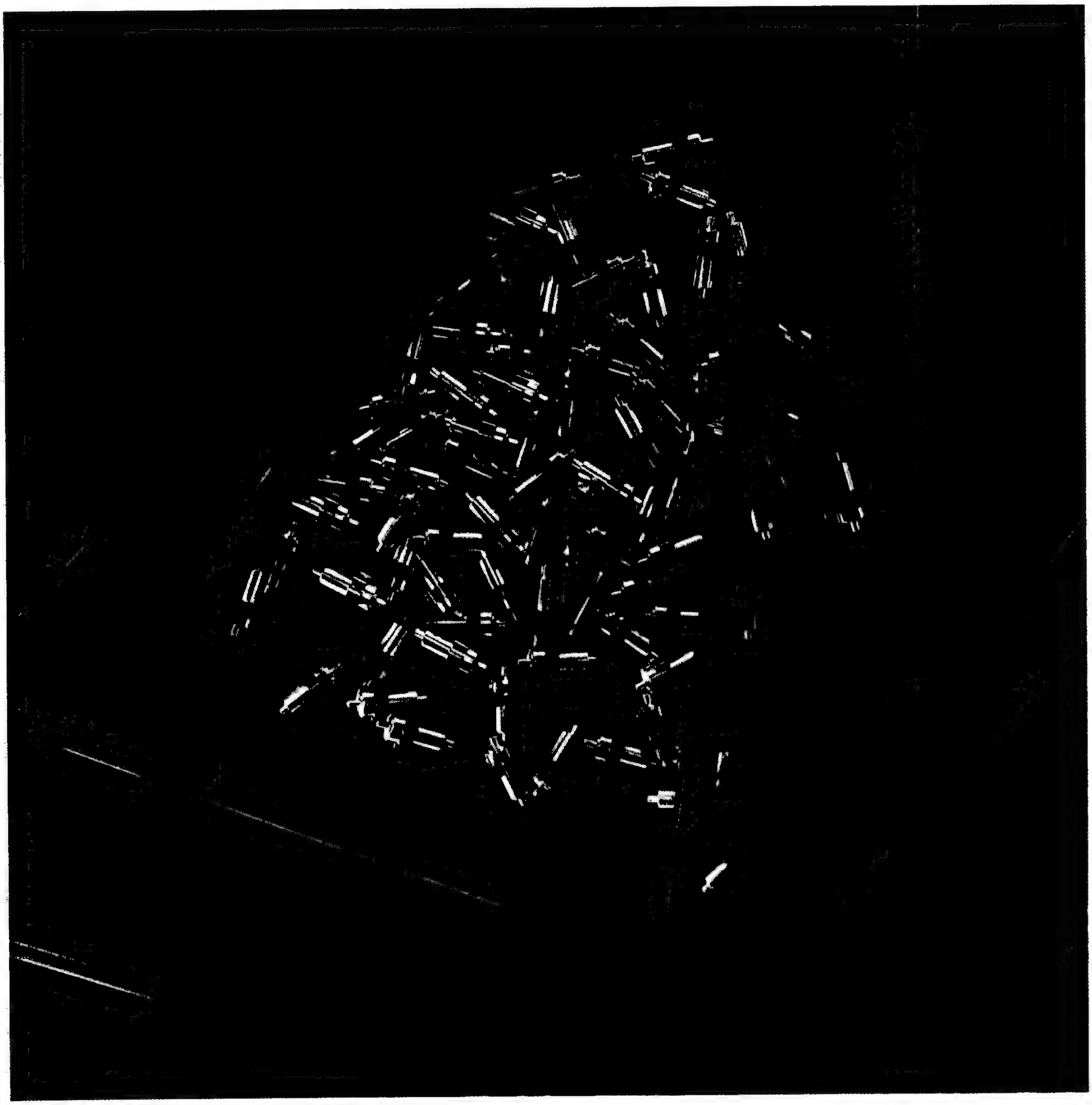
MUNITIONS SUBCOMMITTEE



US Army
ManTech Journal

Finding Alternate Means

Volume 5/Number 3/1980



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US Army

ManTech Journal

Volume 5/Number 3/1980

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ABOUT THE COVER:

Production lengths of precision pinion stock formed by warm hydrostatic extrusion followed by a single cold sizing pass are shown along with individual pinions finish machined from the stock. This new manufacturing technology for making precision pinions from AISI 416 stainless steel for artillery fuzes was developed for ARRADCOM by Battelle's Columbus Laboratories. The main goal of this program was achieved—i.e., to reduce this Government's dependence on foreign made hobbing equipment and carbide hobbing cutters currently used in machining pinions from solid rod stock. A preliminary economic analysis also indicated that the new process is cost competitive with the present hobbing process. The specific pinions shown are used in the ET, M724 fuze system. The new manufacturing process can be used to make other pinions shapes or other complex profiles required for a variety of applications. (Photo by Curtis Scott of Battelle-Columbus' Houston office.

Comments by the Editor

RAYMOND L. FARROW

It is most gratifying to receive commentaries from readers concerning our change of format in the U.S. Army ManTech Journal, as discussed in Issue 2, Volume 5. In that particular issue, we outlined several new approaches to be taken in providing more effective and efficient information transfer and we are continuing to follow these guidelines. We, too, will add still other new touches to the publication as new suggestions are received. We plan to start our guest editorial features in the forthcoming 1981 issues; one suggestion we recently received was from the head of a technical library of an aerospace manufacturing firm, in which he asked that we include the volume and issue number of that particular issue on the inside front cover page under Contents. This would aid librarians to catalogue titles in their respective referencing systems, so you will see this accommodation in all future issues of the Army ManTech Journal.

We wish also to express our appreciation to Dr. Lloyd L. Lehn, Office of the Under Secretary of Defense, Research and Advanced Technology, for his suggestions regarding our statement of purpose on the back cover. Dr. Lehn's comments are the basis for the change in emphasis in this statement to the achievement of increased payback from Manufacturing Technology Program investments—toward more cost effective production base investments by both the military and the private sectors.

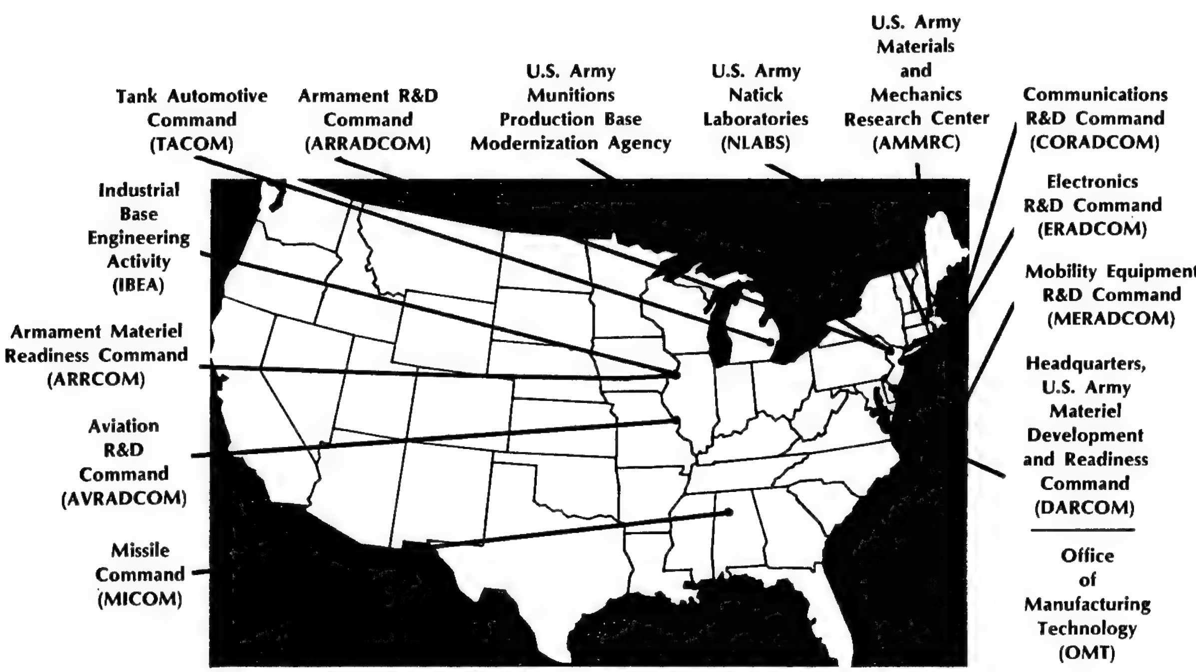
The staff of the Journal also is involved in planning various conferences on manufacturing technology within the structure of the DARCOM commands. Such a conference is the upcoming Tracked Combat Vehicle Manufacturing Technology Conference which is scheduled for June 29-July 1, 1981 at the Hyatt Regency Hotel in Dearborn, Michigan. Hosted by the U.S. Army Tank Automotive Command, this should prove to be another highly informative meeting covering the many problems associated with production of our armored forces' equipments. We wish to call particular attention to this announcement in the hope that all those who are involved with manufacturing technology related to these or similar problems will plan to attend and participate in the discussions.

This issue of the ManTech Journal features another new approach toward notification of readers of important new items of interest. Such is the announcement of the demonstration next June 15 of the world's largest die casting die in Toledo, Ohio. This item is discussed in considerable detail on pages 26 and 27, and it is our hope that the importance of this new development will bring a large number of attendees to the demon-

stration. The impact of such technological achievements by our military/industrial partnerships will be felt dramatically, as indicated in the section on the amortization of the die's cost. This form of announcement represents another first for our magazine.

Other articles in this issue also represent some technical breakthroughs of potentially monumental proportions. The article beginning on page 3 about the new technique of hydrostatic extrusion of precision pinions illustrates a classic example of how manufacturing technology programs can overcome a potentially disastrous vulnerability in our production base capability. No longer will our ammunitions production have an Achilles heel such as having to rely on high skill, high precision machinery that is acquired from an area of the world that lies dangerously close to opposing forces. Other articles provide enlightening information on a wide variety of subjects—a precision ring rolling process developed by General Electric; a more practical, safer new target practice projectile; development of the largest two roll forming machine ever built; cast superalloy aircraft engine frames and casings; more efficient utilization of Titanium supplies by a new isothermal forging technique from TRW; a high rate production method for coating printed circuit boards; and a highly superior new superplastic forming/diffusion bonding technique for joining titanium alloy. These articles constitute a mass of information of very high density for inclusion in one publication, and we trust our readers will find much of this information useful in their own respective work.

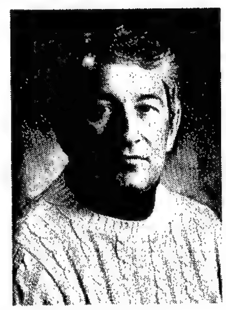
DARCOM Manufacturing Methods and Technology Community



Hydrostatic Extrusion of Precision Pinions

An Alternative to Foreign Dependency

ROBERT J. FIORENTINO is a Program Manager with Battelle's Columbus Laboratories. He directs research in advanced metalworking process development and among his areas of relevant expertise, are conventional extrusion, hydrostatic extrusion, hydrostatic forming, coextrusion of tubular and metal-matrix composites, extrusion cladding, and the role of residual stresses and die design in the extrusion of brittle materials. He has directed studies in conventional and/or hydrostatic extrusion of a wide variety of materials, including Al alloys, Cu alloys, Cu heat pipes, steels, maraging steels, TRIP steels, Inconel 600, Inco 718, Be, Ti alloys, Zr, Zn alloys, U alloys, metal-matrix composites, and multifilament superconductors. Mr. Fiorentino is a holder or coholder of numerous patents on metalworking processes. In addition, he has numerous technical publications which cover various areas of advanced metalworking process development. Mr. Fiorentino is a member of the Extrusion and Drawing Committee of ASM and a member of the executive committee of the American Tube Association. He is also a member of Phi Lambda Upsilon national honor society and a registered professional engineer in Ohio. He received his B.S. in Metallurgical Engineering from Rensselaer Polytechnic Institute in 1952 and his M.S. in the same field from Ohio State University in 1960.



E. GARLAND SMITH, JR. is a Research Metallurgist in the Metalworking Section of Battelle-Columbus. His research experience has been in materials processing and evaluation during his 25 years at Battelle. Specific technical areas in which he has worked include powder metallurgy, solid-state joining, high-energy-rate metalworking and fabrication and high-strain-rate testing. While most of his work in these areas was on specific practical applications, Mr. Smith has contributed to more basic programs which were designed to study process fundamentals and material behavior. During the past eight years, he has been engaged in research relating to conventional metalworking and hydrostatic extrusion. Mr. Smith has authored numerous papers on materials processing. He is a member of the American Society for Metals and the Sigma Xi Society. He acquired a B.S. in Metallurgical Engineering from Virginia Polytechnic Institute in 1956 and an M.S. in Metallurgical Engineering from The Ohio State University in 1964. While in the military service he received a B.S. in Meteorology in 1959 from The University of Utah.

In a process development study for the U. S. Army Armament Research and Development Command (ARRADCOM), researchers at Battelle's Columbus Laboratories have successfully fabricated precision metal pinions for artillery fuzes using hydrostatic extrusion techniques in combination with conventional drawing and machining operations. The U.S. military uses large quantities of these pinions in various mechanical timing devices. In the event of mobilization, the pinions will be vital to defense efforts with production needs climbing to over 40 million a month. Since present hobbing methods for pinion manufacture require machines and precision carbide cutters that are made abroad and that could be unavailable during an international crisis, an alternative method of manufacture is needed.

In the newly developed process, slender billets are extruded into long pieces of profiled but oversize stock. This stock is then cold drawn to precision, target profile dimensions in a single operation. Individual pinions are then finish machined from this stock in an automatic screw machine.

NOTE: This manufacturing technology project that was conducted by Battelle's Columbus Laboratories was funded by the U.S. Army Armament Research and Development Command under the overall direction of the U.S. Army Office of Manufacturing Technology, DARCOM. The ARRADCOM Points of Contact are Frank Ruhmann and David Reap, (201)328-6704 and (201)328-3298.

Process conditions were established for two specific pinions made from AISI Type 416 stainless steel (416 SS) and a small production run was made on one of these. The extrusion process is flexible, however, and can be adapted to other pinion shapes or other similar parts for non-fuze applications, either military or commercial. A preliminary economic analysis indicates the process is cost competitive with present hobbing techniques.

Alternative Process Vital

There are actually two factors that make it undesirable to continue the dependency on foreign-made equipment. One, as mentioned, is the potential vulnerability to international politics. Various situations could adversely affect the accessibility of new equipment and spare parts for maintaining existing facilities. A second factor—perhaps more significant in the long-term—is the general business decline within the watch industry, which threatens the future availability of specialized machining equipment and associated manpower skills currently used to manufacture pinions.

This situation is not new. In the early 1970's it prompted an in-depth study of the production base for manufacturing precision pinions within all branches of the military complex. Based on the results of this study, the decision was made to develop alternative methods and processes for pinion manufacture that would utilize domestic equipment and skills.

In 1973, the National Academy of Science (NAS) funded a series of studies to evaluate four candidate processes—chemical etching, powder metallurgy, die casting, and hydrostatic extrusion. Results of these programs indicated that only hydrostatic extrusion offered enough promise to warrant further development.

Early Programs Attack Problems

In response to the NAS study, the Army funded a study at Battelle in which the feasibility of using hydrostatic extrusion to produce the pinion for the MTSQ, M564 fuze system was demonstrated. This precision fine tooth pinion represents the type used by the Army in clocks and in safety and timing fuzes for ordnance applications. The results of this study demonstrated that a single postextrusion drawing operation was required to produce finished stock with the required tolerances on profile dimensions.

Further Development

With feasibility demonstrated, a follow-on developmental program was conducted which was aimed at optimizing procedures and parameters for making several different pinions. Both warm extrusion and room temperature extrusion were investigated. Program objectives were to

- Optimize the process for the M564 pinion.
- Apply and optimize the process for other pinions (the M724 pinion was used.)
- Evaluate tool life.
- Analyze manufacturing costs.

The results of this program can be summarized as follows:

- The combination of hydrostatic extrusion drawing, and machining provides a viable alternative method of manufacturing pinions for mechanical fuzes.
- Extrusion tooling and process parameters have been optimized for warm hydrostatic extrusion of M564 and M724 pinion stock suitable for drawing and machining into finished pinions.
- Extrusion of up to 130 m (425 ft) of precision M724 pinion stock in repetitive runs through a single die demonstrated satisfactory performance of the extrusion process and tooling in a prototype production run on laboratory equipment.
- A manufacturing cost analysis indicates that this alternative approach should produce pinions at a cost competitive with that for the current process of hobbing.

Actions Recommended

Battelle believes that implementation of this alternative manufacturing method will reduce Government dependence on foreign hobbing equipment. In addition, it will alleviate the problem created by the growing U.S. shortage of people with the critical setup skills needed to operate this equipment.

Accordingly, Battelle has recommended that a prototype extrusion facility should be designed, built, tested, and ultimately installed in an industrial metalworking plant with drawing facilities. This action would provide the opportunity to prove out the facility on an actual production basis so that, in case of mobilization, additional facilities built would be based on a proven design. Ultimately, several extrusion facilities would be needed to meet projected mobilization requirements.

Why Hydrostatic Extrusion?

Hydrostatic extrusion (HE) has certain features that make it ideal for this application. Conventional extrusion, on the other hand, could not be adopted to this need. The essential features of the conventional and hydrostatic extrusion processes are illustrated in Figure 1.

In conventional extrusion, the billet is upset and forced against the container bore before it is extruded through the die. The pressure required to extrude the billet depends on several factors, one of which is the friction force generated between the billet and container. Since this friction force is proportional to the billet-container contact area, the pressure required to extrude the billet depends on billet length and diameter. As the billet length to diameter (L/D) ratio increases beyond certain values, pressures become excessively high and can prevent extrusion. Even with billet lubrication, billet length is limited to 3 or 4 times its diameter in conventional extrusion.

These limitations on billet length do not apply to hydrostatic extrusion. Here, the billet is surrounded by pressurized fluid that prevents any contact with the container bore. Thus friction between the billet and container is completely eliminated, and billets of any length theoretically can be extruded without affecting pressure requirements. The absence of billet-container friction and the added benefits of the pressurized fluid in reducing billet-die friction result in substantial reductions in pressure when compared with conventional practice for the same extrusion conditions.

These beneficial features of HE are vital to the manufacture of pinion stock, which requires the use of long, slender billets (L/D ratios over 100:1) to produce useful product lengths of 3 to 4 meters (10 to 12 feet). With hydrostatic extrusion, the added benefits of forced lubrication help to maximize the extrusion ratio achievable for a given pressure level, or minimize pressure requirements for a given ratio. Die life, in turn, should increase with improved lubrication and reduced pressure requirements. These considerations led to the selection of hydrostatic extrusion for processing pinion stock.

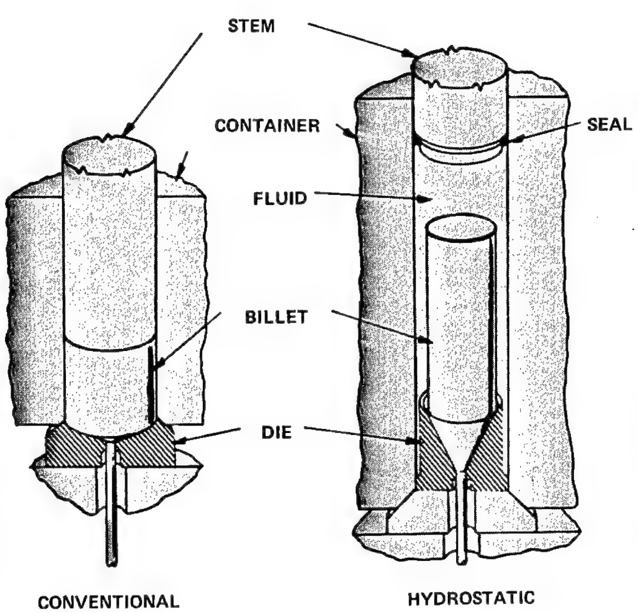


Figure 1

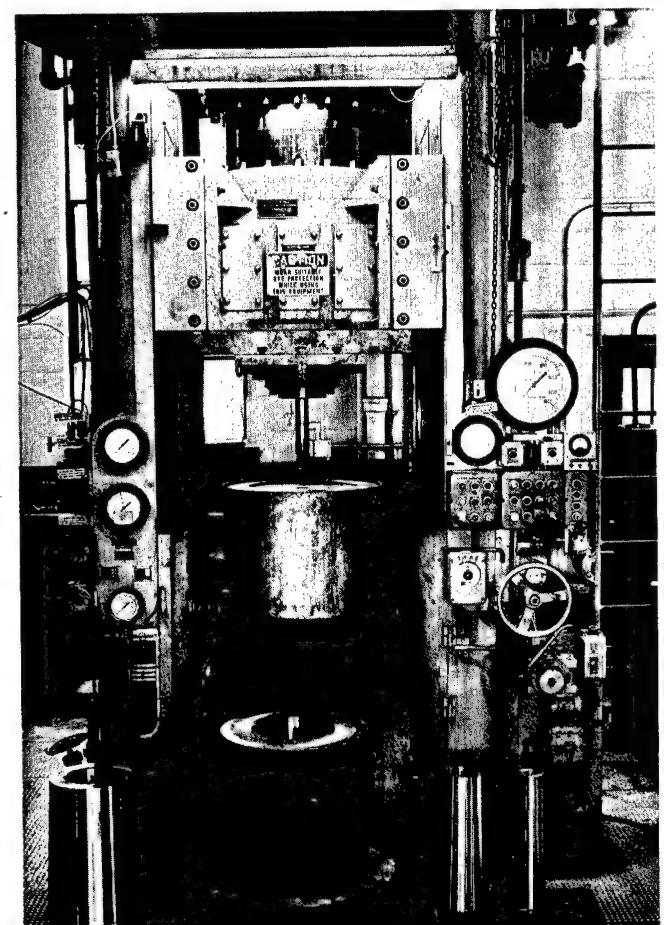


Figure 2

Equipment and Tooling

The major items of equipment and tooling needed to extrude pinion stock are a vertical hydraulic press, a multiple ring container with interchangeable step bore liners and matching stems, and tooling for support of the extrusion die insert.

The 7MN (700 ton) vertical hydraulic press used in the Battelle program is shown in Figure 2 along with hydrostatic extrusion tooling. (One container system is installed in the press and another is disassembled in front of it.) A schematic drawing of the tooling is shown in Figure 3.

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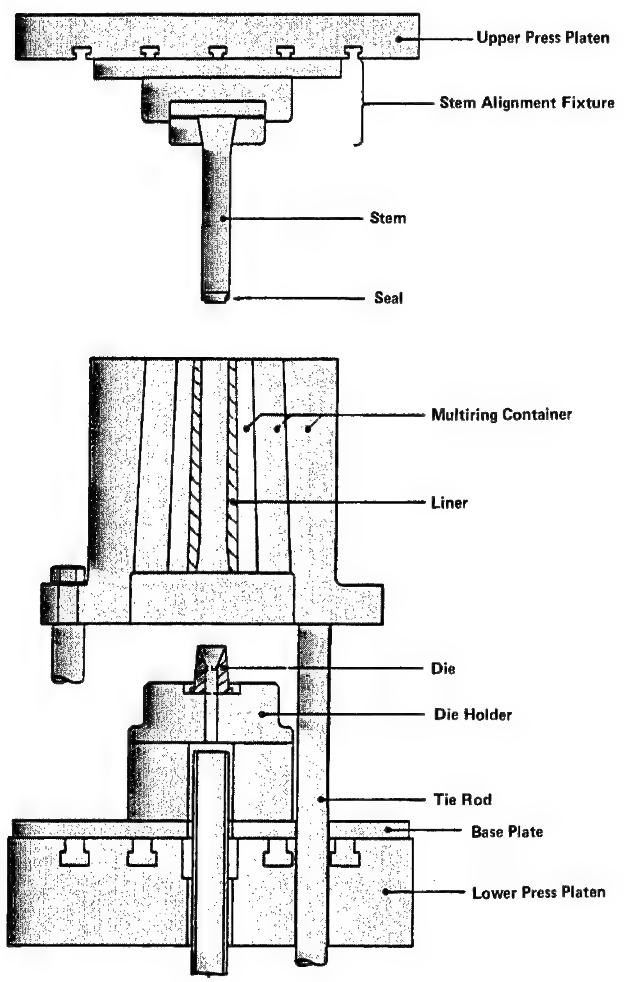


Figure 3

This tooling is positioned on the stationary lower platen of the press. The ram or stem is attached to the movable upper platen. The ram speed can be controlled at rates of 2.5, 8.5, and 34 mm/s (6,20, and 80 ipm). Although a large press was used in the program, only a 2 MN (200 ton) press would be required for a production facility.

Container Tooling

The particular container used in this program was originally designed with a bore diamater of 60 mm (2⅜ inches) and length of 500 mm (20.0 inches). However, this bore diameter was too large for the relatively small diameter billets of less than 13 mm (½ inch) diameter required to produce pinion stock for two important reasons:

(1) The "hydraulic ratio" —i.e., the ratio of cross sectional areas of the stem (and mating bore) to that of the billet—would be so large (e.g., about 25:1) that control of billet extrusion without stick-slip would be difficult.

(2) The large volume of fluid would quickly chill the relatively small billet, normally preheated to 800 C (1470 F), and raise the extrusion pressure requirements excessively.

Stick-slip is especially prevalent when billet lubrication is poor or marginal and the billet does not extrude until an excessive buildup of pressure is developed in the fluid. When the billet finally begins to move, the excess pressure is suddenly released and the billet moves extremely fast until the excess energy stored in the fluid is expended. When this occurs, it is difficult to prevent unintentional complete extrusion of the billet. Furthermore, dimensional variations along the extruded product result.

Container Modification

In order to overcome these problems, Battelle modified the container to keep excess fluid volume to an absolute minimum. This was done by using an additional liner with a step-bore design, as shown in Figure 4. The top bore of the step-bore liner was designed with the minimum diameter and length necessary to extrude most of the billet, leaving behind a butt about 13 mm (½ inch) long. For example, in the setup to extrude 6 mm diameter by 380 mm long (¼ by 15 inches) billets, the top bore was 19 mm in diameter by 100 mm long (¾ by 4 inches).

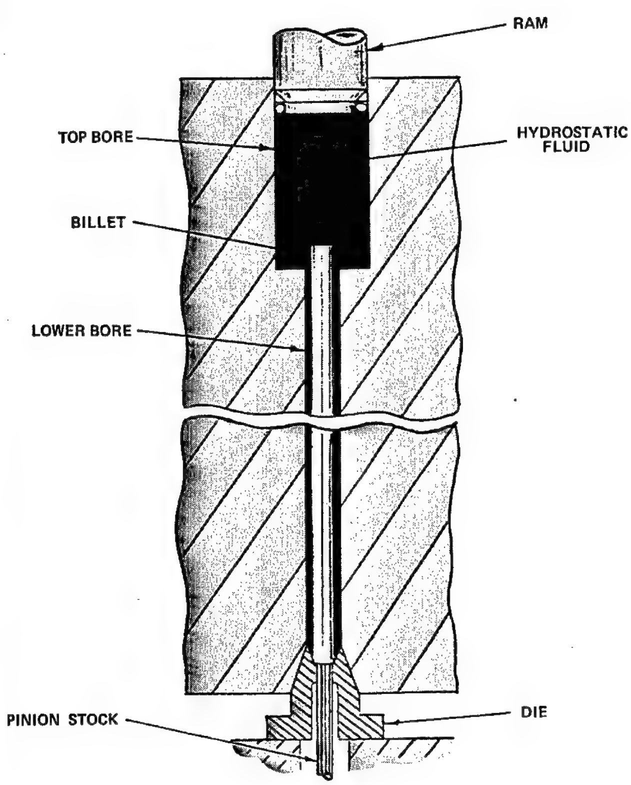


Figure 4

The "hydraulic ratio" of the stem/billet cross sectional areas in this case is only 9:1 compared with 90:1 for the original bore diameter of 60 mm (2⅜ inches). Minimizing the amount of fluid to this extent keeps the stick-slip and billet chilling problems within acceptable levels.

Although a very high hydraulic ratio obviously is undesirable, a ratio of 10:1 is absolutely essential for extrusion of long, slender billets (with an L/D of 100:1 or more). For example, at a hydraulic ratio of 10:1, only 100 mm (4 inches) of stem travel is required to extrude 1 m (40 inch) long billets. A billet of this length is required in a production facility to produce—at an extrusion ratio of 3:1—pinion stock sufficiently long to be fed into the automatic screw machine. Thus, the hydrostatic extrusion process with a properly designed step bore container is an absolute requirement for successful extrusion of long, slender billets into suitable lengths of pinion stock.

Tooling Design Important

A cross sectional view of the die stack is shown in Figure 5. The most important components are the **die insert** and the **insert holder**. The backer and die support serve to transfer extrusion forces to larger areas, thus reducing the bearing stresses below the die. The die holder houses the remaining components and is used to accurately locate the die concentric with the container bore.

Looking at the insert holder function, the large external taper mates with a matching taper on the liner bore. Pulling the container downward against this tapered interface creates a mechanical press-fit seal that prevents fluid leakage during extrusion. The internal converging taper of the insert holder provides a conical lead-in surface to the die insert. This surface, which has an included angle of 45 degrees, provides an effective fluid seal with the billet nose.

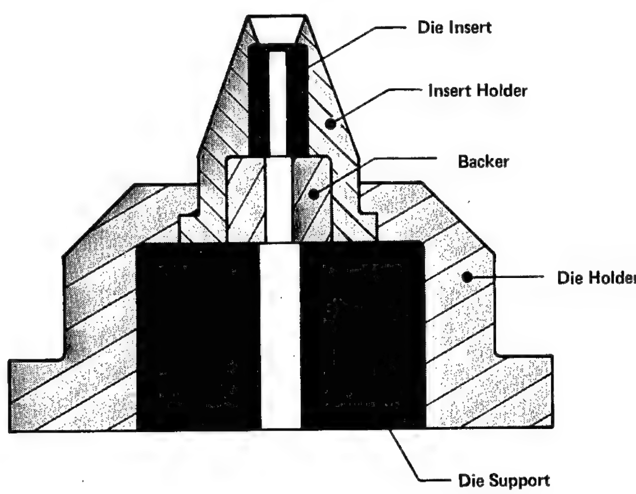


Figure 5

Five Basic Operations

Using this equipment, pinion manufacturing requires the following sequence of operations:

- Preparation of billets
- Hydrostatic extrusion to provide oversize pinion stock

- Drawing of pinion stock to final profile dimensions
- Machining of discrete pinions from the drawn stock
- Heat treatment of finished pinions.

Most of the experimental work in this and earlier programs was directed toward billet preparation and hydrostatic extrusion, since these operations required more development for this particular application. In contrast, the drawing, machining, and heat treating steps are largely established commercial processes and required little or no further development.

Optimizing The Process

Battelle's development of this process involved two phases—process optimization for the M564 pinion and optimization for other pinions, including a production run of the M724 pinion. In the first phase, the objective was to build on the processing experience gained in earlier programs and to refine the procedures and parameters for extruding and drawing pinion stock suitable for feeding into automatic screw machines.

In the optimization studies, the desire to simplify the extrusion operation as much as possible prompted early attempts to develop a room temperature process for extruding 416 SS pinion stock. A belief that effective billet lubrication could be achieved more easily at room temperature also encouraged these trials. Although these efforts were successful, extrusion required high pressures that posed a threat to die life. Consequently, attention was turned to a warm extrusion operation. For extrusion, the billet, die tooling, and working hydrostatic fluid were preheated to lower the billet flow stress for extrusion. The same die design features and billet lubrication parameters found most effective in the room temperature trials were used. A typical cross section of the M564 pinion after extrusion is shown in Figure 6 (a). The results of these extrusion trials confirmed that elevated temperature processing was an effective way to reduce pressures and promote longer die life.

Several lengths of pinion stock produced in these trials were cold drawn in a single pass to required dimensions. Samples were taken from the drawn material to evaluate dimensional uniformity. The dimensions of the drawn stock were found to be within those specified for the M564 pinion. In addition, the circularity of the pinion teeth was found to be within the limits necessary for adequate feeding of this stock into automatic screw machines. A typical profile of drawn M564 pinion stock is shown in Figure 6 (b).

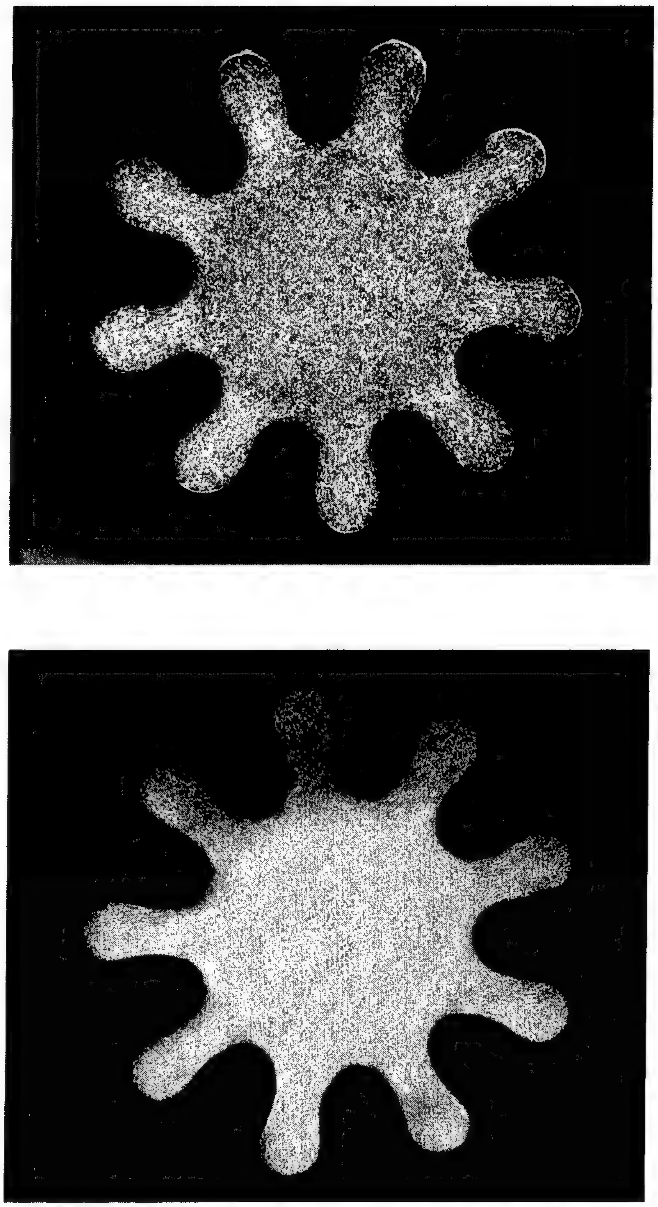


Figure 6

Die Life Satisfactory

The useful life of the extrusion die insert is one of the most important cost factors affecting this pinion manufacturing process. The optimized warm extrusion conditions established for the M564 pinion were used in a series of trials to evaluate the die wear characteristics.

A die made from Ferro-Tic HT-6A was selected for study. Successive trials were run with 416 SS billets at a nominal 4:1 ratio. Die wear was monitored by measuring the average minor diameter of the die orifice after each trial using a set of plug gauges.

Some 50 m (165 feet) of product was extruded through the die before one of the teeth broke off, preventing further use. Plots of average minor diameter at the die orifice as a function of cumulative product length for this die (No. 15) are shown in Figure 7. This data shows that most die wear occurs during the early stages of use. This result probably reflects the initial rounding off of asperities on the teeth to some stable size that then resists further change.

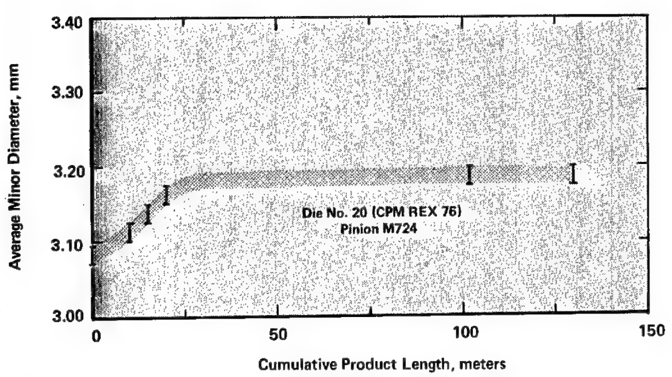


Figure 7

M724 Production Run

With successful extrusion of the M564 pinion, attention was turned to producing stock for other pinions using the manufacturing technology already developed. At the Army's request, efforts were concentrated on the pinion for the ET, M724 electronic fuze system.

As a starting point, the extrusion procedures and parameters successfully used to produce M564 stock were applied to the M724 pinion. Using these conditions, however, extrusion of this smaller pinion at a 3:1 ratio could not be achieved at an acceptable pressure level. Extrusion took place, but at high pressures, 1500—1750 MPa (220-250 ksi) and with stick-slip conditions occurring in several trials.

This periodic stick-slip problem led to further efforts to improve billet lubrication. Poor adherence of the lubricant coating was suspected because in many trials the coating washed off the billet. Results of tests confirmed that lubricants having a resin type binder consistently stayed on the billet through simulated extrusion operations. The best results were obtained with a lubricant having an alkaline silicate binder.

Additional extrusion trials using billets coated with this lubricant resulted in generally reduced pressures. Stick-slip conditions were either prevented or reduced to acceptable levels. Typical cross sections of M724 pinion stock are shown in Figure 8 (a) (after extrusion) and in Figure 8 (b) after drawing.

After optimizing the process for producing M724 pinion stock, an extended "production" run of approximately 200 extrusion trials with laboratory tooling was made to gain additional operating experience and produce a quantity of stock to process into finished M724 pinions. These trials also permitted evaluation of die performance over an extended period and a study of process sensitivity to changes in extrusion conditions that would make it more amenable to a production environment.

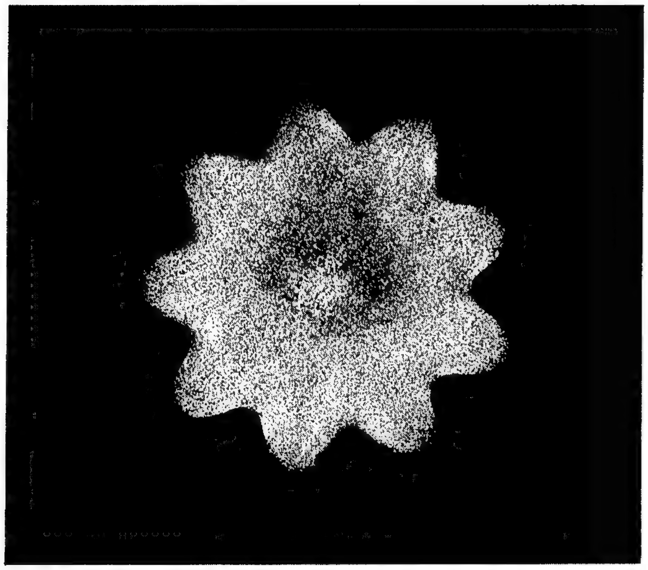
Die Performance Satisfactory

Die performance in the production run was evaluated by measuring orifice wear and by visual inspection. In addition, 50X profiles of pinion stock taken from each die at various stages of the run were measured and compared to determine changes in dimensions that would reflect wear at the die orifices.

Die performance is indicated by two curves in Figure 7 (Dies 20 and 23). These results show that extrusion die made from CPM REX 76 should produce a minimum of 130 m (425 feet) of pinion stock. Most of the die wear occurs early, reflecting the rounding of small asperities that then resist further change.

Particularly gratifying was the fact that the dies were free of cracks and still functional following this production run. This result may be attributed to the use of a rigid holder that improves die support during use. The fact that 130 m (425 feet) of stock can be produced with a single die suggests that a useful die life corresponding to about 150 m (500 feet) of stock may be a reasonable expectation.

Approximately 125 m (410 feet) of M724 pinion stock from the production run was drawn by Rathbone Corporation and supplied to Devon Precision Industries for final machining into discrete pinions.



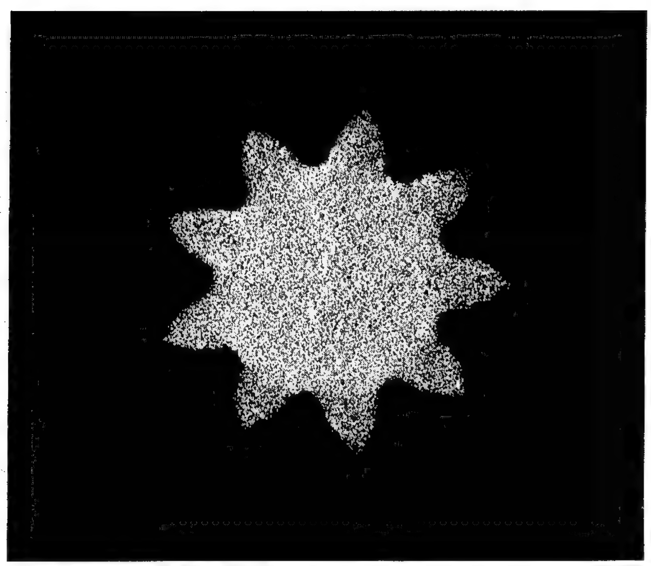


Figure 8

Process Cost Competitive

A final assessment of the newly developed process was that of cost. The estimated cost of manufacturing M564 and M724 pinions was calculated based on available data. The extrusion, drawing, and machining parameters assumed for production purposes were:

Billet size		
Length	1 m	40 in.
Diameter	6mm	0.25 in.
Extrusion ratio		3:1
Extruded product length (usable)	2.92m	115 in.
Assumed butt loss	13mm	0.5 in.
Assumed pointing loss	90mm	3.5 in.
Drawing reduction		17%
Drawing ratio		1.2:1
Drawn product length	3.51m	138 in.
Pinion blank length	10mm	0.4 in.
No. of pinions/billet		345
No. of pinions/hr.		10,350

An extrusion production rate of 30 cycles/hr is relatively modest and should be easily achieved in production. The last item, "no. of pinions/hr", means that the extruded stock produced in an hour should yield 10,350 pinions after drawing and finishing.

Using these parameters, pinion cost was estimated for three levels of production:

	Estimated Cost per 1000 $
● Single order (500,000 pinions)	72.77
● Peacetime (2,000,000 pinions/mo.)	70.28
● Mobilization (over 40,000,000 pinions/mo.)	64.23

The estimated total pinion cost for a single order buy of 500,000 pinions is $72.77/1000. This is fairly close to the cost of $70.28/1000 for peacetime quantities of 2,000,000 pinions/mo. The cost of about $70/1000 for peacetime quantities compares favorably with one commercial estimate of $95/1000 for hobbing the M564 pinion. The pinion cost in mobilization quantities of over 40,000,000/mo. is estimated at $64.23/1000.

It is clear that this alternative manufacturing approach may very well be cost competitive with the current method and in some cases may be cheaper. However, the overriding consideration for implementing this new method should be that—in the event of mobilization—it provides a backup technology that would preclude our dependence on foreign hobbing equipment, foreign tungsten carbide hobs, and critically short setup skills.

G. E. Process Slashes Costs

Engine Components Precision Ring Rolled

By Willard Hansen
General Electric Co.
Lynn, Massachusetts

Using a patented ring rolling process that they developed, General Electric is able to cut manufacturing costs on superalloy engine ring components by as much as 60 percent. At the same time, starting material requirements are only one half to one eighth those for conventionally machined rings. The attractive cost benefits are brought about by the reduced material requirements, together with reductions in labor hours and a lower capital investment. G.E. has demonstrated that this innovative process is applicable to many ring shapes in the aircraft industry. It should be readily adaptable to similar components for other products.

Less Material, Greater Production

By far the most significant cost savings are associated with reduced material input for large rings manufactured from high cost materials. With significantly less starting material, both material costs and machining time are slashed. To illustrate the potential here, material and cost savings on two configurations to which the process has been applied are shown in Figures 1 and 2.

Capital costs are also significantly lower because a ring roll machine has about twice the production capacity of a vertical turret lathe used for conventional machining of rings. As a result, for an equivalent number of rings, the capital investment for ring roll equipment is about one half that normally expected for conventional machining equipment. Hot working techniques are now being developed that should further enhance both the process capabilities and the potential savings of precision ring rolling.

Costs Per Machined Parts Soar

Gas turbine engines have numerous ring shaped components in the form of flanges, seal backing rings, combustor panels, and other related shapes. These ring components are used throughout the engine and are welded into major fabricated components. Typically, the rings are made from nickel and cobalt base alloys such as Inconel 600, Inco 718, Hastelloy X, Haynes Stellite 188, and Rene 41.

NOTE: This manufacturing technology project was funded by the General Electric Co. The U.S. Air Force Materials Laboratory currently is funding a program with G.E. on the hot working of preforms. The Air Force Project Engineer is Kent Kojola, AFML, Wright-Patterson AFB (513)255-5037.

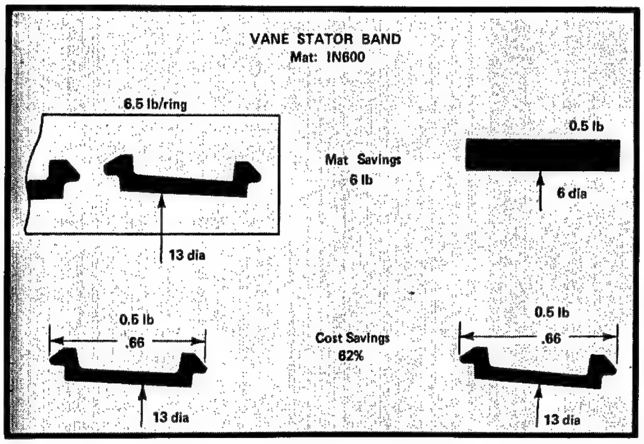


Figure 1

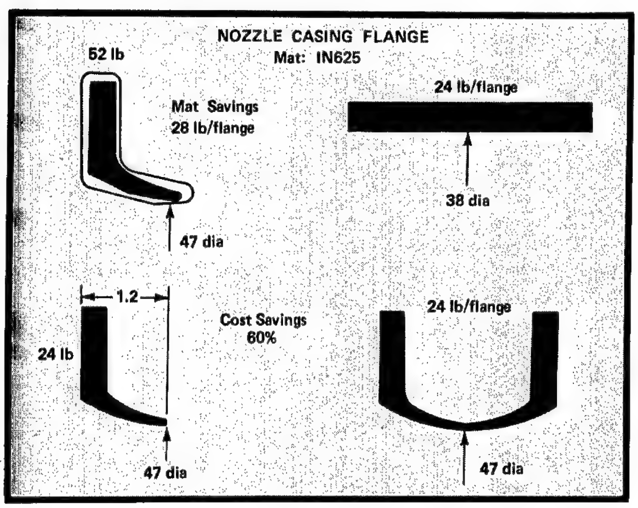


Figure 2

Such parts generally are machined from ring forgings or flash welded rings, starting from blanks with a rectangular cross section. Designers must provide a substantial material envelope to allow for process tolerances. The ratio of starting material to material in the final part after machining normally ranges between 2/1 and 10/1, but it can be even greater for very complex shapes. In a large gas turbine engine, a typical 50 inch diameter flange ring weighing 25 pounds after machining will require about 60 pounds of starting material. The cost of removing this excess material and the additional waste in the form of chips is significant. With both energy and superalloy raw material costs steadily inflating, a concerted effort is needed to improve the material utilization factors for these alloys wherever possible. Precision ring rolling offers such improvement.

Flow Control the Key

Precision rolling of a ring shape usually involves several roll passes and anneals designed to achieve gross material distribution within the ring cross section. The early roll passes transform a commonly available starting blank into a precision preform for the final ring roll sequence. To accomplish this, precision ring rolling combines existing industrial capabilities with a novel idea for rolling precision shapes in ring form.

Rolling begins with a controlled amount of input material weighing about the same as the final configuration. The starting blank may have a round or rectangular cross section and, in some cases, may have some limited contour. The starting bar shapes are cut into precision lengths, hooped into a ring, and flash welded. Sufficient material is provided to compensate for material loss during welding. After welding, the rings are rolled successively in several die sets, each die bringing the part incrementally nearer net shape. Intermediate anneals are applied as required. During rolling, the ring cross section is reduced approximately 0.002 inch for each revolution or roll pass. Typically, the ring rotates ten revolutions per minute during rolling. The key to precision ring rolling is the slow material flow in three dimensions. With proper selection of dies, substantial transverse metal flow across the face of the roll die is obtained. After the final rolling pass, the part is precision expanded to obtain the final diameter. Some typical cross sectional shapes that are precision rolled are shown in Figure 3.

Precision Increased

The process has several unique characteristics and capabilities. In addition to providing excellent material utilization, it is extremely precise. Ring contour can be maintained within 0.002 inch. Larger rings are expanded to a diametral tolerance of ± 0.010 inch and several smaller rings are manufactured to diametral tolerances

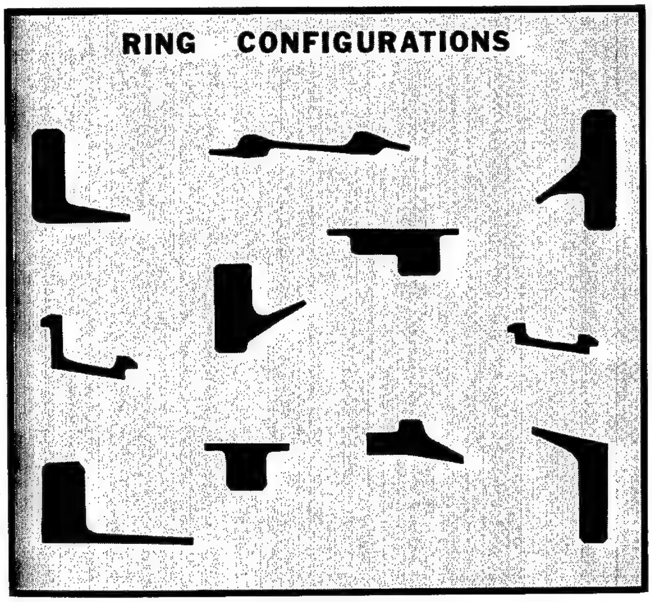


Figure 3

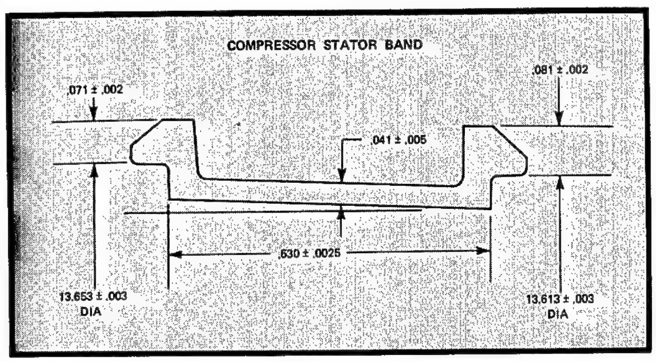


Figure 4

of ± 0.003 inch. The flatness of the rolled rings is outstanding. For example, when a 50 inch diameter ring is placed on a surface plate, a 0.005 inch thick shim cannot be inserted beneath it. The surface finish of these parts equals that of the roll die. Because the flash welded areas receive substantial working during rolling, mechanical properties across the weld are equal to those of the base metal. Grain size is controlled through proper selection of annealing temperatures. Figure 4 represents some actual dimensions that are being obtained by precision ring rolling and expanding.

Hot Rolled Preforms

As noted, precision ring rolling requires several passes, with the earlier passes essentially providing a preform. In order to obtain the precision required in the final rolled part, this preform cross section must be dimensionally precise and consistent from ring to ring. When appropriate material distribution in the precision preform is developed, relatively few roll passes are required to obtain the dimensional characteristics of the final part. Thus, the use of a precision hot rolled ring preform can significantly reduce the cost of the precision ring roll process. The reductions of several roll passes can be combined in a single hot roll pass, reducing labor hours and eliminating several cleaning and annealing cycles. Lower rolling loads and improved material flow are other benefits.

Alternative Approaches Possible

Two alternative approaches to incorporating a hot roll pass are being considered and evaluated. The first utilizes the isothermal rolling process developed by Solar and described in a separate article in this issue of the Army ManTech Journal. The second is a modification of G.E.'s established ring rolling process that provides for hot rolling.

In this second approach, an induction coil and a 300 KW induction heater are added to the roll machine. The coil heats a small sector of the ring on the entry side of the reduction rolls and power is applied as the ring rotates. The speed of ring rotation is such that the temperature of the entire ring is raised to the desired working temperature, with only a slight temperature differential on the entry and exit sides of the coil to balance radiation losses. The working temperature is controlled by an infrared sensor that monitors ring surface temperature and automatically adjusts the power required.

When hot rolling techniques are fully developed, precision ring rolling will offer even greater benefits to manufacturers of this type of superalloy part.

Safer, More Cost Effective

New Target Practice Projectiles

The development of a 30 mm nonricochet/frangible target practice (TP) projectile from powder metal (PM) will reduce accidents and save money. Machined steel 20 mm practice projectiles, which posed much less ricochet danger than 30 mm rounds, were the major documented cause of 332 ricochet accidents in aircraft strafing practice missions. Two of these accidents resulted in loss of life and also aircraft.

The 30 mm system which currently is coming into extensive use is the GAU-8 gun shown in Figure 1. Tactical Air Command (TAC) chose to develop a non-ricochet/frangible projectile for the GAU-8 gun; the production processes for the prototype could be applied to 20 mm systems as well. Additionally, production costs would be lowered, saving an estimated $38.4 million on the price of the 30 mm projectile alone over a 15 year buy period.

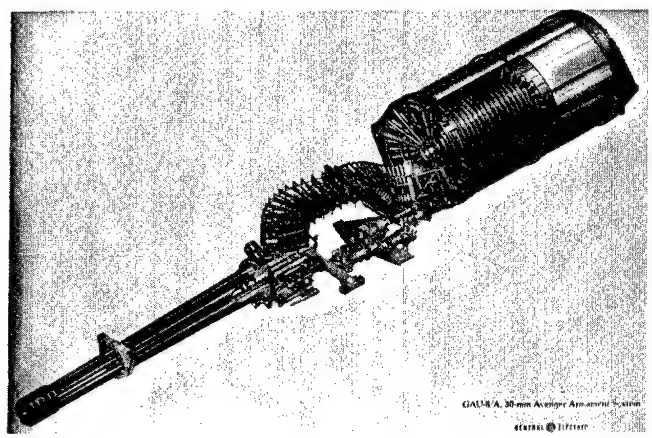


Figure 1

CLIFFORD A. KELTO currently is Product/Market Development Manager for the Micrograin Products Division of Kelsey-Hayes Company. He came to Kelsey-Hayes early this year from the Manufacturing Technology Division of the Materials Laboratory, Air Force Wright Aeronautical Laboratories, where he specialized in powder metallurgy and intermetallic materials. Educated at the University of Michigan (B.S. in Chemistry, B.S.E. in Materials Engineering), Mr. Kelto joined the Air Force Materials Laboratory as a failure analyst in 1973 and served as part of the Laboratory's Corrosion Control/Failure Analysis group until 1978. His publications cover a wide variety of metallurgical subjects, including aerospace applications of titanium alloy powders, PM products in munitions, failure analysis and aircraft accident investigation, fatigue and microstructure, corrosion of structural materials, evolution of jet engine materials, scanning electron microscopy, and gas porosity in cast metals. His presentations have included not only published papers, but also unpublished work in novel PM consolidation methods and failure findings and recommendations up to the four star level within the Air Force. Mr. Kelto has made numerous presentations to both civilian and military audiences on the subject of Failure Analysis and Air Force service experience with various weapons systems. His professional society affiliations include the American Society for Metals, Society for the Advancement of Materials & Process Engineering, National Association of Corrosion Engineers, the American Foundrymen's Society, and the Procrastinators Club of America.

Risks Even Greater

The A-10 aircraft which uses the GAU-8 gun was designed for close air support of ground forces and flies more slowly than most aircraft carrying 20 mm weapons. Sorties are closely spaced, so when the A-10 finishes a target practice pass, the chances of a ricochet strike from a trailing mate are even greater than for fighter planes with 20 mm systems. Additionally, GAU-8 TP steel projectiles have three and a half times the mass of 20 mm slugs, so although both exit the barrel at about the same speed, the 30 mm impact velocity is significantly higher on long standoff shots, increasing the ricochet potential

NOTE: This manufacturing technology project that was conducted by the U.S. Air Force Armament Test Lab, Eglin AFB, was funded by the U.S. Air Force Materials Lab, Wright-Patterson AFB. The AFML Project Engineer is Francis H. Froes (513)255-4018.

at low incident angle delivery. Due to its higher momentum, the larger projectile goes farther and higher than the 20 mm round, dramatically increasing the danger to both aircraft and the surrounding range. Figure 2 shows that, at a given obliquity, a 30 mm TP projectile can travel nearly four miles downrange. For rigid steel targets, impact of the standard machined steel projectile produces a near elastic collision, with the slightly deformed body "skipping" off the surface at an angle roughly equal to the incident angle. The projectile remains intact, spinning and ballistically true. Figure 3 shows the condition of such a projectile before and after target impact. For soft, inhomogeneous surfaces such as earth or macadam, the projectile usually also remains intact but, depending on obliquity, may bury itself. Alternatively, the attacked projectile may dig a trough and glance off at a higher than incident angle, or it may burrow for several feet before reappearing to leave the surface at any angle.

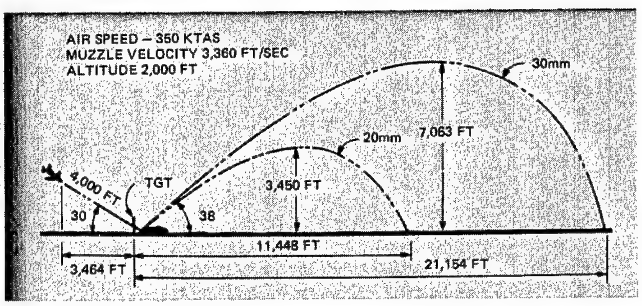


Figure 2

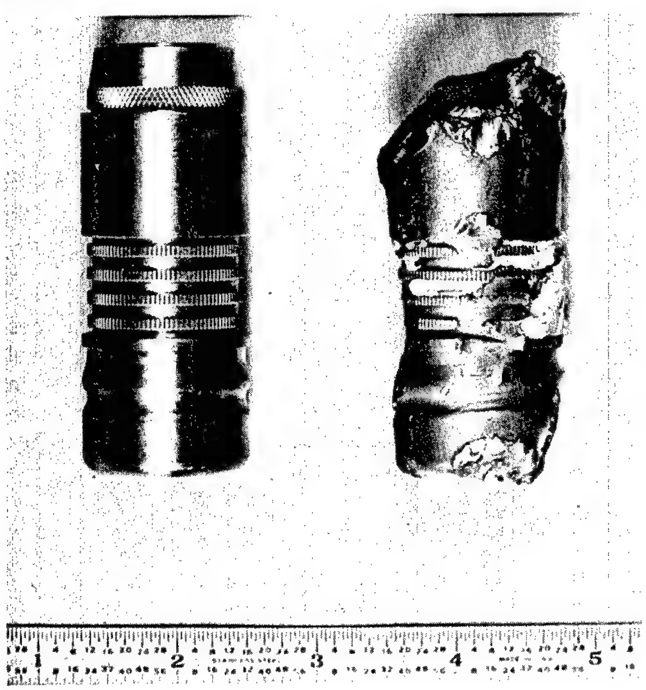


Figure 3

Few Solutions Provided Early

The Air Force Armament Test Laboratory (AFATL) at Eglin AFB, Florida, has been developing frangible projectile designs for several years. One early concept in 20 mm bullets was to die cast the body from zinc alloy, first with an integral zinc rotating band, then later with a plastic rotating band injection molded into a recessed band seat. Unfortunately, accuracy was affected by ballotting and rifle engraving of the walls of the soft zinc material, and rotating bands were lost during cold and hot firing tests. Figure 4 depicts 20 mm projectiles in flight, showing borrelet engravings and "chunking" of the rotating band. Additionally, the cartridge crimp was loosened during handling and chambering of rounds, due to the low strength body material. A modified design (Figure 5) utilized an expensive stainless steel bore rider to reduce engraving, but the bore rider was sometimes lost in flight (Figure 6), and accuracy was not improved. However, the use of the zinc somewhat improved impact breakup compared to steel.

Another design concept, applied to both 20 mm and 30 mm projectiles, was to injection mold a glass reinforced Mylar body around a column of stacked washers, as seen in Figure 7. Impact with the target or ground would

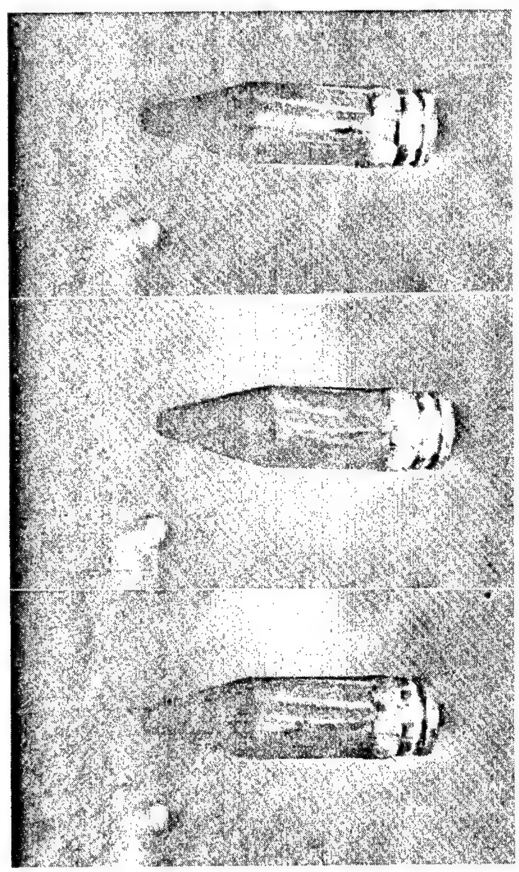


Figure 4

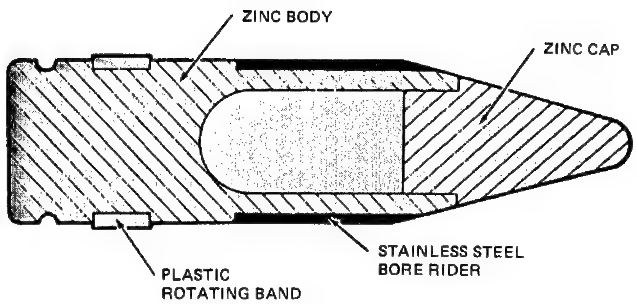


Figure 5

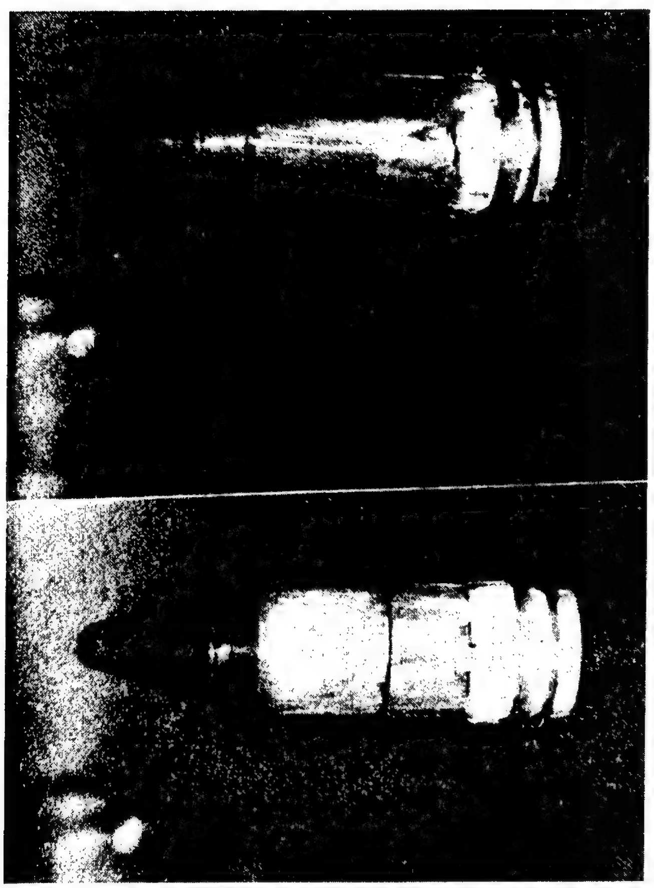


Figure 6

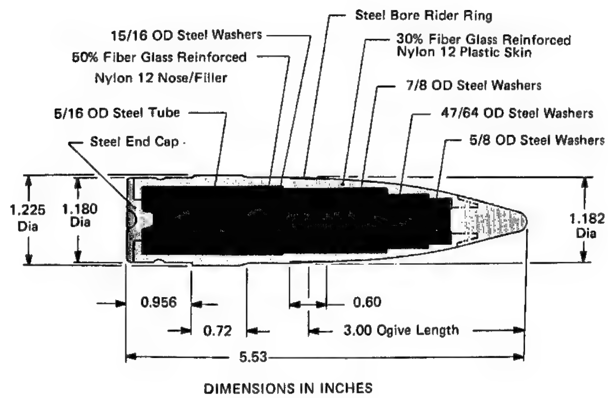


Figure 7

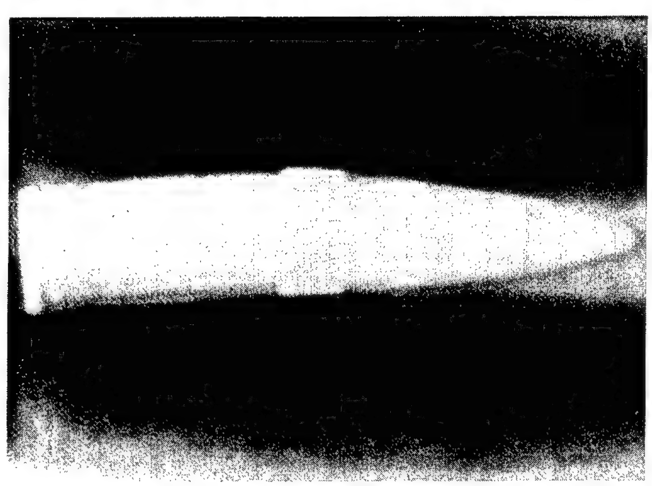


Figure 8

rupture the plastic case of the projectile, spewing the washers which, because of their low mass and tumbling flight, would carry only a short distance. Several technical problems have resulted, however, the primary one being premature projectile breakup during gun launch. It was caused by ballotting in the barrel (damaging the plastic body), which resulted from variations in mass properties: the washer column was not concentric, and a large bending stress resulted from the rotation of even a small (0.010 inch) column eccentricity. Figure 8 is an in-flight flash X-ray photo illustrating the response to such loading just prior to failure.

To hold concentricity, a steel center tube was adopted which firmly maintained the positions of the washers during manufacture. Eccentricity between tube ID (tooling reference during molding) and OD (washer index) resulted in some structural problems, but eventually 100 percent structural integrity during launch and flight was achieved. Unfortunately, the stiffened assembly also exhibited resistance to impact breakup and had accuracy problems.

PM Proposals Solicited

Feasibility studies by industry showed that a design which incorporated the advantages and properties of powder metallurgy (i.e., high material utilization, little or no machining to produce the desired shape, and control

of tensile strength and toughness by manipulation of final density) could produce accurate, low cost frangible projectiles with good in-flight structural integrity. When the Air Force Materials Laboratory solicited proposals for a manufacturing technology program in 30 mm non-ricochet TP projectiles, three different offerors responded with steel PM concepts, resulting in a multiple contract award.

The three successful bidding companies (Aerojet Ordnance, Avco Systems Division, and Honeywell Defense Systems Division) had divergent approaches to the design and production of a frangible projectile. However, the final product in each case was a steel part which matched the armor piercing incendiary 30 mm round both ballistically and in external dimensions. It weighed approximately 5800 grains and was fabricated from PM steel with a post-sinter density of 0.82—0.85 times the theoretical density (density of solid steel). The presence of pores throughout the PM microstructure facilitated breakup on impact with even "soft" surfaces such as sand. Fragments from an early PM design which exhibited reasonable frangibility are shown in Figure 9. Note that, except for the base, no cylindrical sections remain.

For low velocity, low angle shots on soft surfaces, breakup of the massive rear portion (base) of the projectile was difficult to achieve in all three designs. Fortunately, the bases on most sand target shots buried themselves, and those that did ricochet appeared to retain only a fraction of the impact kinetic energy, most of which was expended in breaking up the forward portion of the projectile.

The rough edged pieces formed from the breakup tumble rather than spin, and their aerodynamic instability results in very short ricochet distances. While the designs had no specific technical performance requirements for acceptable frangibility, all three companies worked toward improving their designs to yield—under "worst case" ricochet conditions—fragments no greater than about 15 percent of the total projectile mass.

Production Processes Vary

Presently, standard target practice projectiles are cut and ground to shape from plain carbon steel barstock in a series of screw machine operations. Of the three designs produced, Aerojet's process most closely approximates this method: pressed and sintered PM bars, cut to length and impregnated with a thermosetting resin to improve machinability, are turned on screw machines. The design, shown as a cross section in Figure 10, incorporates stress raising V notches and a deep center bore to aid breakup. Although PM steel in this density range would normally be hard on cutting tools, resin impregnation enhances machining characteristics, resulting in a cost reduction over standard TP projectiles.

Avco cold isostatically presses its projectiles from an iron powder-graphite-binder mixture. The single piece projectile body shown in Figure 11 is formed in a soft "collapsible" tool (Figure 12), which is sealed and contained in an elastomeric bladder in a high pressure hydraulic vessel. This "dry bag" isostatic method yields green parts which, when sintered, have very uniform density throughout and require little or no grinding to reach external dimensions. The isopress method is economical because of its simplicity, but the loading-pressing-unloading operations are very time consuming and must be revamped to be cost effective.

Honeywell uses the most complex design and processing plan. Their projectile is shown in Figure 13 and consists of a two piece PM body (sleeve and base) fitted

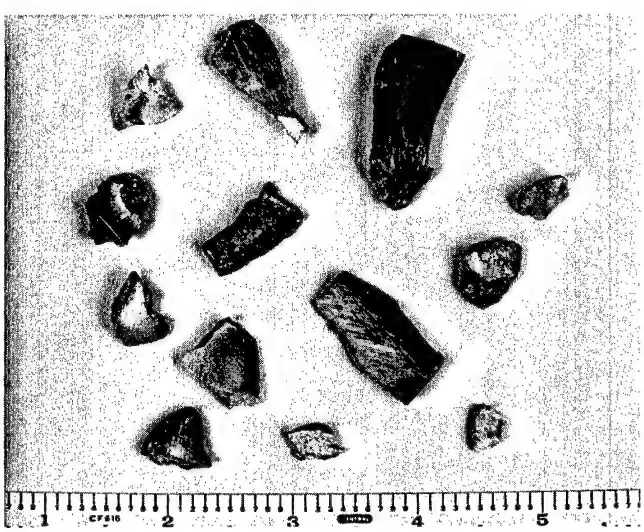


Figure 9

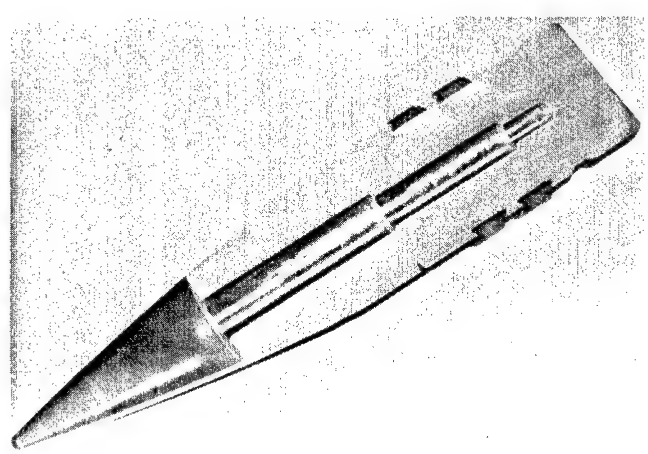


Figure 10

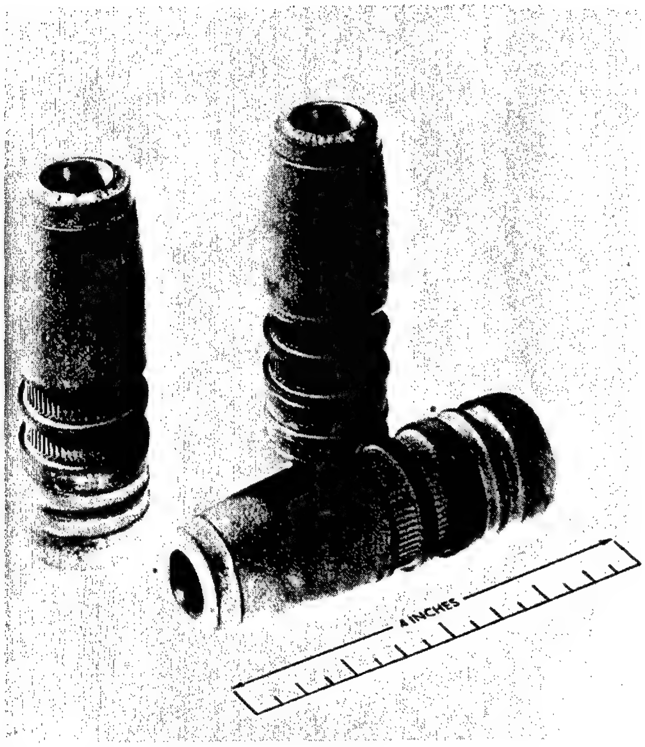


Figure 11

Figure 12

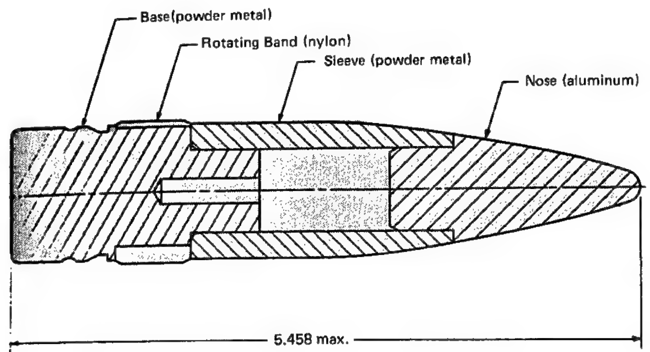


Figure 13

with an aluminum nosepiece. The body parts are mechanically pressed from an iron-graphite powder mix, sintered, and interference fit assembled. Honeywell obtains a "chipless" round with a large potential cost savings by rolling rather than machining the crimp groove into the base.

Three Prototypes Tested

The Air Force Materials Laboratory frangible target practice projectile production effort was conducted in cooperation with the A-10 System Program Office Armament Division, and consisted of two phases. Phase I involved the generation of a steel PM design from a low cost design concept. This was not an easy task, for air deployed projectiles have very stringent requirements for structural integrity in flight, and even pieces of the nylon-glass rotating bands can do damage to turbine engines if ingested. Therefore, after laboratory fabrication of the three projectile prototypes, several tests were performed and the designs subsequently modified and retested for improved results. Tests for structural strength during firing for accuracy, flight stability, and bullet pull (the tensile force required to separate projectile and cartridge case) were conducted in accordance with current TP specifications.

All three projectile makers experienced difficulties during Phase I. For example, at some point in development, all three designs partially or completely lost their plastic rotating bands (Figure 14). This phenomenon was caused by any of a variety of obvious or subtle factors—e.g., band thickness, bevel, or strength; band seat design; and test temperature. In the case of the machined PM bar design, band "chunking" during firing of some rounds was attributed to below optimum density in the PM body material under the band seat. The drop in modulus that accompanies a decrease in density in PM material produced larger than expected radial expansion of the band seat as the round spun up in the barrel, forcing the rotating band more tightly into the rifling and, in some

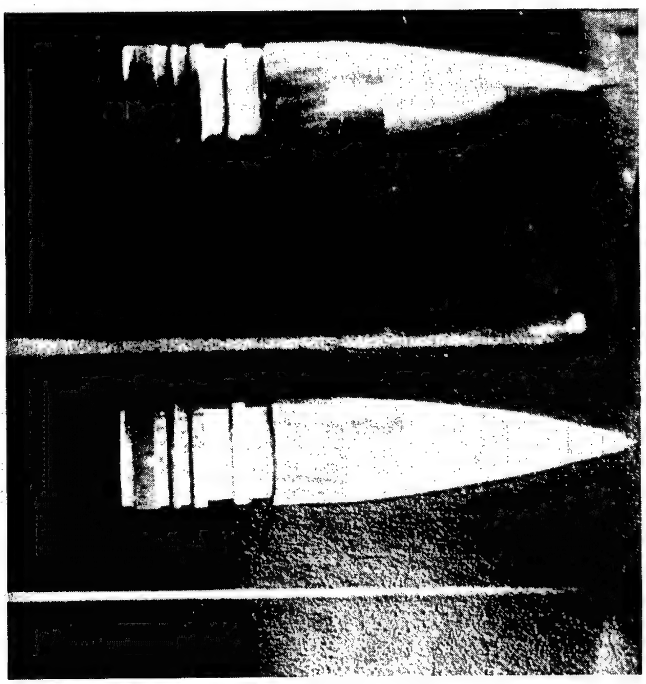


Figure 14

cases, ripping pieces off. A slight increase in as-sintered bar blank density solved the problem.

"Too Clean" A Phenomenon

A mysterious loss of some rotating bands was noted late in the Phase I development of the isostatically pressed design. Other projectiles in the same "defective" lot which had been immersed in oil as an ancillary experiment had no rotating band losses. The problem was traced back to the addition of an extra degreasing step following compaction which eliminated residual oils from the pores of the base. It was a strange case of a product being too clean. Without the oil or Loctite, chamber pressure was transmitted through minute connective porosity paths to the band seat where it blew the bands off, or forced their expansion so that they were torn off by the barrel rifling. The oil effectively sealed off the rotating band seat region from the very high (60,000 psi) chamber pressures which act on the base during firing, without adversely affecting paint adhesion. Fixing the problem was quite simple and required no design changes.

Synchroballistic photographs of the mechanically pressed projectile assembly during the early part of the program revealed an interesting phenomenon: it was, in flight, not an assembly at all, but a disassembly of the base and the sleeve, as seen in Figure 15. This "premature frangibility" would probably not pose a hazard to the deploying aircraft, since both sections were spinning and stable in flight, but accuracy might be affected (two hits, or misses, per round fired), and structural

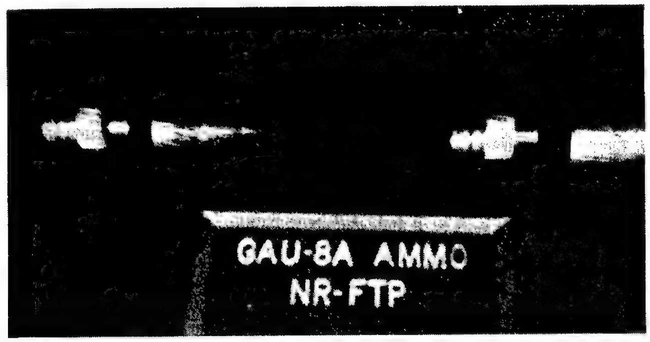


Figure 15

integrity requirements did not allow for the disassembly process. An obvious solution would be to sinter the two parts together.

Full Spin Enlarges ID

However, it was decided to investigate the reason for the separation before deciding upon a course of action. A finite element stress analysis was performed on the base stub and mating sleeve, utilizing such parameters as density and hardness as functions of position from the base of the sleeve and elastic modulus and yield strength as functions of density. The analysis showed that, for the density of material used, the sleeve inner diameter was increasing 0.0015 inch at full spin. In addition, the yield strength of the hollow base stub was exceeded during press fitting, resulting in 0.002 inch permanent diametric set. These combined deformations produced a slip fit instead of an interference fit when the projectile reached maximum spin (near the point of muzzle exit), and the slight drag of the rotating band attached to the base pulled the stub from the sleeve. The solution was to eliminate the stub hole, increasing its section size, along with increasing the sleeve density. This avoided the problems of double sintering or "green assembly" and the possible breakup resistance associated with sintered assemblies.

After repeated design changes and testing, several hundred "improved" projectiles of each design were fabricated. Only minor process refinements were implemented in pilot production. The purpose was to

- Establish production processes
- Test for structural integrity and accuracy
- Ricochet test at 10 degree graze angle, 2500 ft/sec, against armor steel, sand, and macadam targets.

In order to provide control for comparative testing, the Air Force Armament Test Laboratory (AFATL) at Eglin AFB, Florida evaluated all three types of projectiles to corroborate the successful results reported by each contractor (no cross testing was performed between

contractors). AFATL collected data on preliminary automatic gun firings, mass properties, in-flight structural integrity, and impact fragmentation and dispersion. All three designs maintained structural integrity when fired at a high rate from a GAU-8 gun, and each design exhibited marked improvement in fragmentation when compared with standard TP control specimens fired under identical conditions. Table 1 is a summary of data on weights and numbers of fragments collected from the tests. Figure 16 shows a plot of calculated fragment trajectories (for Aerojet rounds) and compares them with the 30 mm trajectory of Figure 2. The results of the tests, the designs, and the manufacturing and quality assurance plans were evaluated by the Air Force for continuance in the program's second phase.

Projectile Type	No. of Rounds	No. of Fragments[a]	Average Fragment Weight (gr)	No. of Fragments 100 gr	Average Weight of Fragments 100 gr
Steel impact target					
Aerojet frangible	10	680 (68)	57.2	112	267.2
Avco frangible	9	284 (32)	122	83	349.8
Honeywell frangible	10	233 (23)	169.6	90	385.7
Standard	5	58 (12)	288.9	36	455.8
Sand impact target					
Aerojet frangible	6	209 (35)	1,449.2	64	370.4
Avco frangible	6	351 (58)	2,513	46	421
Honeywell frangible	6	311 (52)	2,950.1	36	606.8
Asphalt impact target					
Aerojet frangible	6	158 (26)	129.4	55	328.8
Avco frangible	6	186 (31)	120.9	42	454
Honeywell frangible	6	166 (28)	123.5	44	398
Standard	2[b]	10	412.5	10	525

[a] Average number of ferrous fragments per projectile is in parentheses.
[b] One Honeywell and one Aerojet projectile.

Table 1

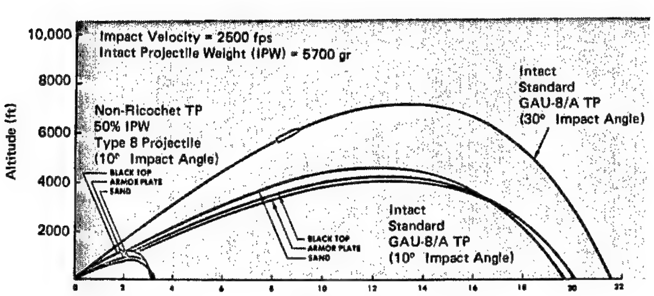


Figure 16

Tests Result in Program Revision

Phase II was an optional effort originally intended for only one contract producing the lowest cost projectile design (cost projections were made for production rates of 50,000,100,000, and 200,000 per month) of acceptable structural integrity, accuracy, and nonricochet characteristics. It called for pilot production of at least 20,000 projectiles in four lots, with in-process, nondestructive inspection. One thousand projectiles would be Loaded, Assembled, and Packed (LAP) to make live rounds and subsequently tested. Test data from Phase I, however, indicated that all three final designs exhibited good technical performance. Cost projections, without even pilot production, were too uncertain to warrant elimination of any of the designs from consideration. Consequently, all three designs were carried into Phase II. Since the original Phase II test plan was not sufficiently comprehensive to fully qualify a frangible TP design for use by TAC, Phase II was redirected. The redirection included LAP of all 20,000 projectiles of each type and additional testing for full qualification for production and use.

In the new Phase II effort, each company will produce, inspect, and perform in-process firing tests on 20,000 of its own originally designed projectiles. The program plan calls for obtaining qualified production LAP for all projectiles and testing by all potential suppliers and purchasers.

Qualification testing is complicated for two reasons. First, Aerojet and Honeywell are currently the only qualified suppliers of GAU-8 ammunition. They are competitive suppliers of high explosive, armor piercing, incendiary, and target practice loaded cartridges. Avco cannot, therefore, sell cartridges to the Air Force because it does not have a qualified LAP line. Avco's projectile would only qualify by being LAP'd on either Aerojet's or Honeywell's production line. In addition, the latter two might want to use Avco's projectile instead of their own for cost reasons. The result: Avco's projectiles are being LAP'd by Aerojet and Honeywell on their qualified lines, then redundantly tested by Avco and the other suppliers for qualification.

The second factor complicating Phase II production is the requirement of numerous involved qualification tests. Table 2 gives the type and number of Mann barrel (single shot) tests required, all of which are governed by military specifications. In addition, service life tests are performed on six hundred fifty-five rounds of each type, which are handled and chambered repeatedly in the automatic guns and then subjected to controlled environmental tests and subsequent Mann barrel firing. Approximately 2000 rounds are required to complete Mann barrel qualification tests for each projectile design. Automatic gun fire testing is performed in accordance with a "burst schedule" and requires about 7000 rounds of each design.

Each contractor will perform ricochet testing on sand and steel targets. AFATL will perform all ricochet testing

QUALIFICATION, MANN BARREL TESTS (Action time, chamber pressure, muzzle velocity, structural integrity, and protective coating condition are recorded on all Mann barrel firings.)	
TYPE	NUMBER OF ROUNDS
Weight	25
Mass Properties	25
Transportation Vibration	55
Aircraft Vibration	55
Temperature-Humidity-Altitude	50
Accuracy	100
Debulleting	50
Five Foot Drop	50
Waterproofness	50
High Temperature	50
Low Temperature	50
Thermal Shock	50
Humidity	50
Salt Spray	55
(Plus Service Life Tests)	

Table 2

on macadam targets to ensure compositional uniformity. Testing will be done on ranges adhering to the requirements of Figure 17; all three producers will use the test conditions and numbers in Table 3. Of the 18 frangible projectiles fired at each condition and target, 9 will be recorded by high speed photography to determine fragment velocity and dispersion and, for the other 9, fragments will be captured in fiberboard packs to relate dispersion and particle mass. Where the sand cloud may obscure streak camera records, fragmentation of sand impact shots will be recorded by flash X-ray. The spatial distribution and velocity data collected for each design and ricochet condition will be reduced and used to plot fragment "cloud" position versus time. This will aid in establishing pullout maneuvers to avoid flying through a cloud of high angle fragments, which might result from multiple sand strikes.

Phase II also includes a detailed economic analysis of eacy production method, preparation and submission of detailed drawings, an environmental protection plan, a system safety program, and a reliability and maintainability study.

Production Benefits Predicted

Technical performance and cost effectiveness of all three PM steel designs has been encouraging. Estimates

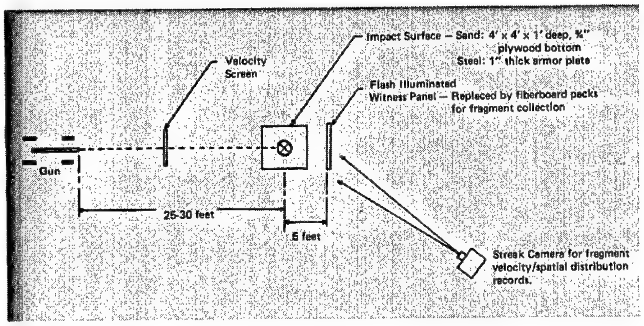


Figure 17

RICOCHET TESTING

- Target surfaces are sand and steel (AFATL to do some macadam testing)
- For each test condition (except high-angle sand shots*) 2 reference rounds (Std TP) and 18 frangible TP rounds will be fired.
- Velocity and spatial distribution of fragments, measured photographically, to be recorded for 9 of the 18 frangible shots.
- Fragments captured and sized on 9 of the frangible rounds, each condition.

CONDITION		
Incident Angle, degrees		Impact Velocity, fps
5		2000
5		3000
10		2000
10		2500
10		3000
30	*(Burying threshold angle in sand)	2000
30	(Steel only)	2500
30	*(Burying threshold angle in sand)	3000

*Burying threshold angle in sand is established for each impact velocity by performing 5 ricochet tests at successively lower incident angles (3^{o} increments) beginning with 30^{o}, until ricochet is achieved.

Table 3

show a per part savings of 54 cents for a high production rate for the least expensive projectile over the standard TP projectile. Current consumption of TP rounds is 3.5 million per year, with an increase to 5 million annually likely by 1985. Interpolating between these production figures for 1979-85, the total savings on the **cost of the projectile alone** over the projected 15 year buy period (thru 1994) is $38.4 million! The savings in aircraft damage and personal injury cannot be calculated.

Giant Two Roll Machine Built

10′ Cylinder in One Piece

The largest two roll forming machine ever built is being developed by the U.S. Army Munitions Production Base Modernization Agency for the second generation of the U.S. Navy's Fuel Air Explosive (FAE II) program. Figure 1 illustrates the FAE II 2000 lb BLU 96/B and the 510 lb BLU 95/B concussion bombs. The 16 ft long, 13 ft deep (including loading tray), 5 ft high machine will weigh 34 tons and will roll form premachined aluminum sheets into BLU 96/B warhead fuel container skins. The initial cost of $300,000 will reap a predicted total savings of $5 million per 100,000 fuel containers, and the machine will pay for itself after production of 5,800 containers.

Previous two roll forming machines were limited to forming machined and/or prefinished sheets up to 6 ft long (Figures 2 and 3). The largest of these machines was 8 ft long, 4 ft deep, and 5 ft high, weighing about 2 tons. The 10 ft cylinders required for the BLU 96/B skins were previously welded together using three individual roll formed sections (2, 6, and 2 ft long) and two weld rings (illustrated in Figure 4). The new machine will roll the 10 ft long, 6.5 ft wide, and 3/16 in. thick premachined sheets into a single 10 ft long, 2 ft diameter cylinder.

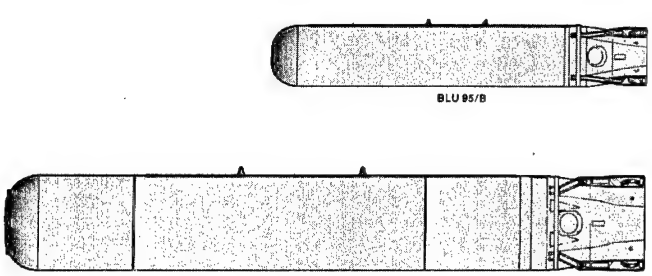


Figure 1

EDWARD CASSIDY is a general engineer at the U.S. Army Munitions Production Base Modernization Agency (AMPBMA) in Dover, New Jersey. His projects include the Army's Family of Scatterable Mines (FASCAM), the Navy's FAE II bombs, and the Air Force's Antiarmor Cluster Munition and Tactical Munitions Dispenser. Mr. Cassidy has also helped to develop various Army nuclear weapons systems and has published 18 reports on nuclear weapon effects, testing, and safety analysis. He received a Special Act Award in 1977 for his work on the Special Stockpile Safety Studies on fielded Army nuclear weapons. Mr. Cassidy received his B.S. from Stevens Institute of Technology in 1963 and has taken graduate studies in mathematics at Seton Hall University. He is a member of the American Manufacturing and Technical Advisory Group (AMTAG) and the American Defense Preparedness Association (ADPA).

Welding Process Expensive, Complex

The results of an economic analysis early in the project show substantial savings if a one piece fuel container could be roll formed. Although the tooling cost for the new machine is greater than that for the three piece welding process, elimination of weld rings (material) and welding (labor) results in significant cost reduction (see Table 1).

Also, the welding process complicates production: four cylindrical welds are required per skin; and each

NOTE: This manufacturing technology project that was conducted by the U.S. Army Munitions Production Base Modernization Agency was funded by the U.S. Army Material Development and Readiness Command under the overall direction of the U.S. Army Office of Manufacturing Technology, DARCOM. The AMPBMA Project Engineer is Edward Cassidy (201)328-4081.

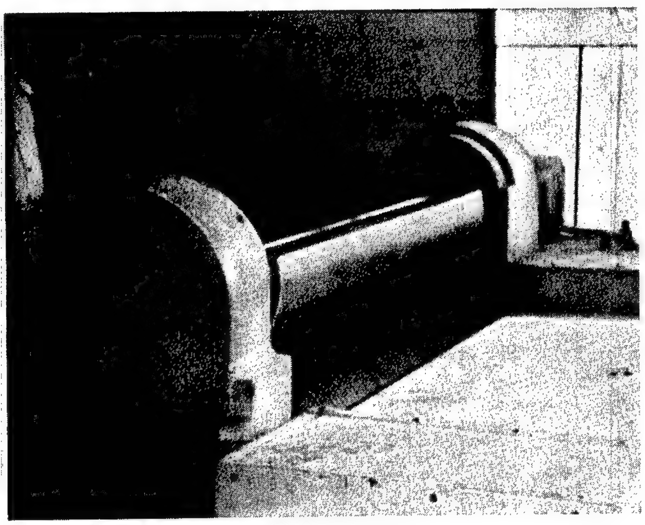


Figure 2

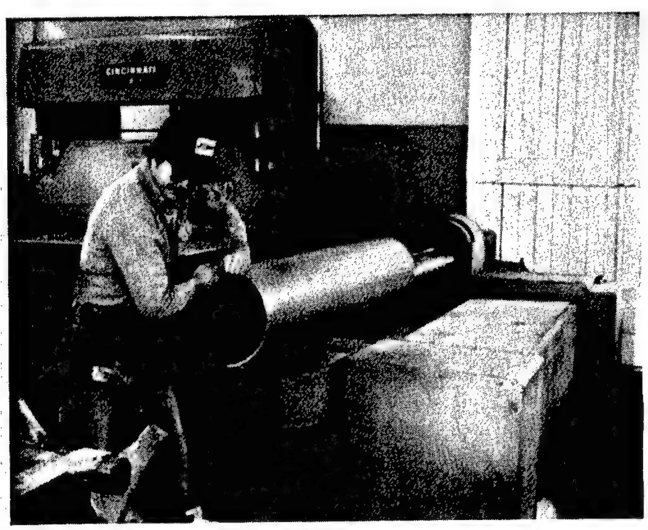


Figure 3

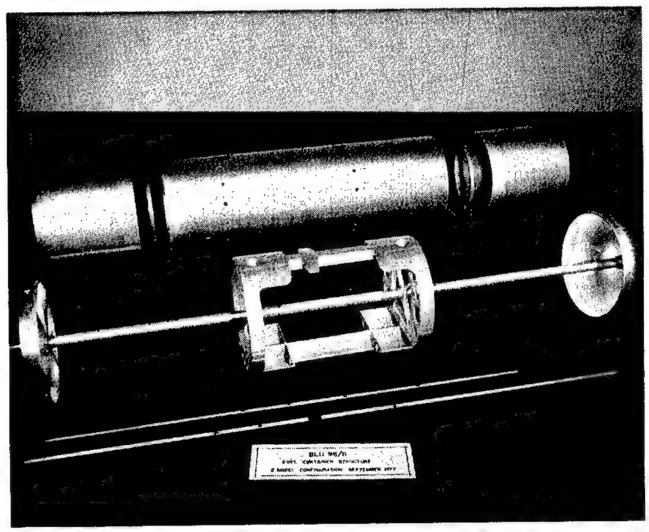


Figure 4

Cost, K FY78 $/100 K Fuel Containers			
	Existing Process	Proposed Process	Savings
Tooling	10	300	(290)
Material	3,980	---	3,980
Labor	7,336	6,006	1,330
		Total	5,020

Table 1

weld must be hermetically sealed to prevent leakage and formation of leak paths from liquid fuel. The one piece container also will allow for smooth interface of forward and aft bulkhead machined flanges and eliminate two of the cylindrical welds.

Two Roll Design Superior

The two roll machine is manufactured with an upper steel roll and a urethane coated lower steel roll (Figure 5). The long lasting load bearing and identical spring back of the K-Prene urethane ensures repeatable roll form curvature. Some rolls have produced over a million parts without requiring replacement.

As the lower roll is rotated, the urethane coating comes in contact with the upper roll and undergoes continuous deformation while maintaining constant volume. Thus, the urethane coating exerts high but uniform counter-pressure, forcing the rolled material to conform to the shape of the upper roll. The urethane returns to its original shape after each contact with the upper roll.

Another method of forming the cylinders had been to use three or four roll machines (Figure 6). However, the two roll application proved to be superior for several reasons:

(1) The two roll process minimizes or eliminates secondary machining usually required for conventional three or four roll models. The latter models can only roll form unmachined skins which are expensive and difficult to produce. Two roll models can form flat, premachined sheets without kinking, fluting, or breaking. The premachined rupture grooves depicted in Figure 7 also remain undamaged. If the sheet is deformed prior to roll forming—i.e., if an edge is bent due to an accidental drop—it is "straightened out" by being wrapped around and forced into the shape of the round, smooth upper roll. The sheet can be run through the machine several times until it is acceptable. This is due to the uniform bending force from the urethene coated roll, which produces a perfect rounded cylinder.

(2) The three/four roll process requires secondary forming of leading and trailing edges due to insufficient contact with the bending roll; lack of formation resulted.

(3) Segments of cylinders or complete cylinders from all types of sheet metal—finished, embossed, perforated, wire mesh, regular or irregular shapes—can be rolled up to 0.25 in. thickness in a single pass between 100 and 350 parts an hour via the two roll process. Protective coatings (such as anodizing, irradiating, or even protective papers used during shipment of highly polished sheets) will not be damaged during this type of roll forming.

(4) Diameters can be adjusted on two roll machines via a slip-on tube over the top roll (Figure 5).

The two roll system is so sensitive to variations in properties that it can detect changes from lot to lot.

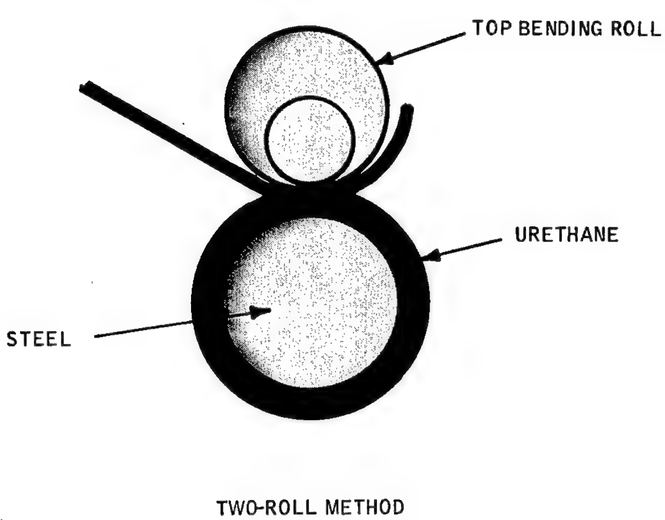


Figure 5

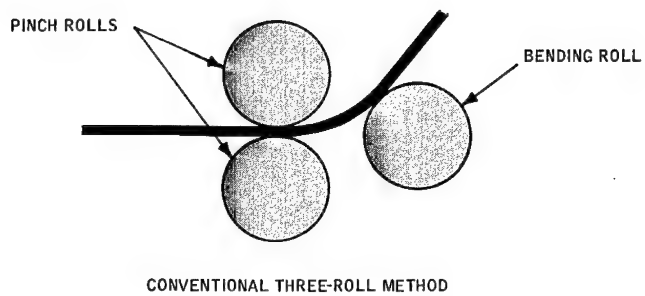


Figure 6

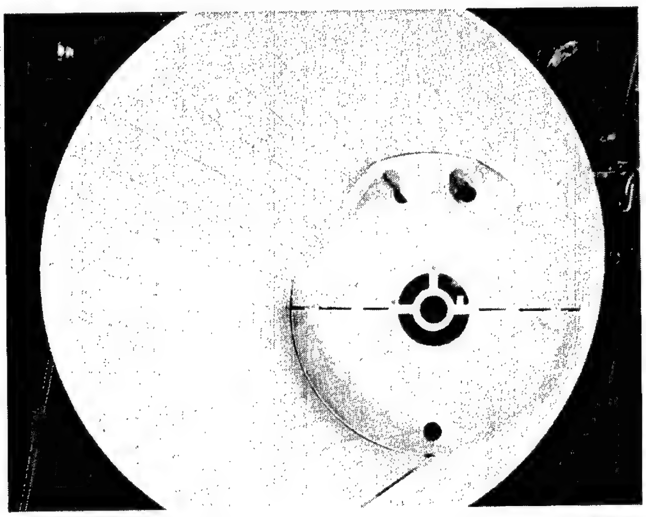


Figure 7

If the rolled part diameters change, it is due to the material and not the machine; the radius of the curved part is controlled by the radius of the upper roll and the material's "spring back" properties. The sheet also can be rerolled until the proper diameter is obtained, if the proper diameter is not achieved on the first roll.

Application Prospects Even Brighter

The advantages of the two roll machine are now possible without the disadvantages of the welding process. The largest two roll machine was demonstrated in October, 1980, and successfully roll formed a one piece BLU 96/B fuel container (Figures 8 and 9). These containers will be manufactured for flight testing of BLU 96/B bombs prior to actual production. The prototype machine alone is capable of making several thousand containers a month and can meet all planned production requirements without replacement or duplication.

Similar machines can be built to roll form sheets up to twenty feet length, according to design data from the prototype. The technology can be used to manufacture cylinders or curved surfaces for aircraft skins, ship hull sections, tubing, truck trailers, fuel storage tanks, etc. All imaginable functions and shapes are possible.

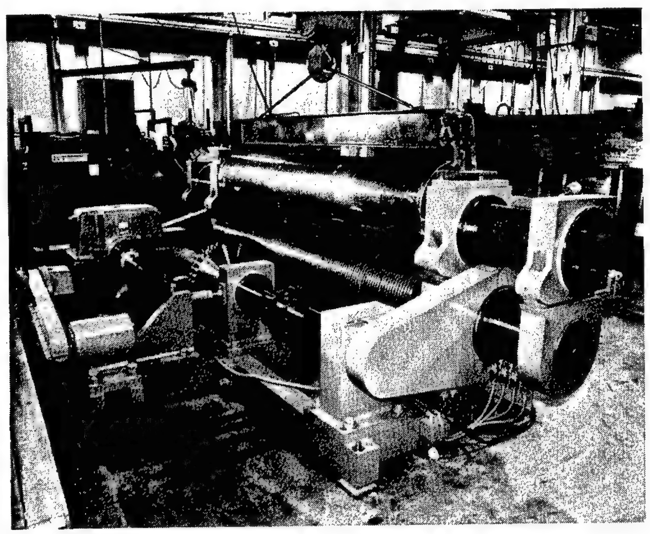


Figure 8

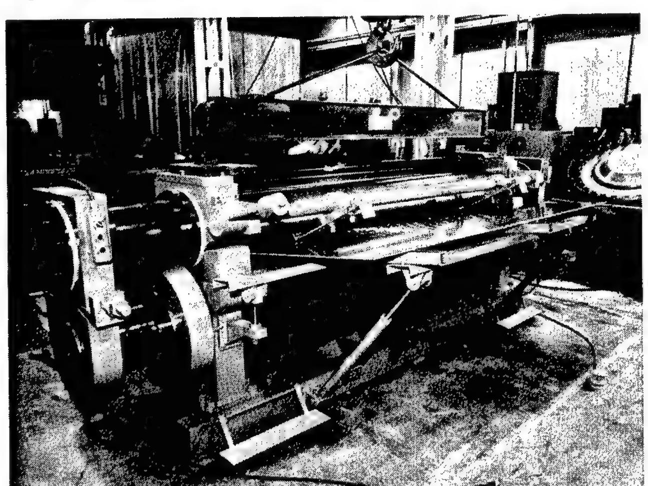


Figure 9

Massive Demonstration Set

World's Largest Casting Die

The largest die casting die ever manufactured is scheduled for demonstration on 15 June 1981 at Doehler-Jarvis, Toledo, Ohio. The U.S. Army Munition Production Base Modernization Agency is developing the die in support of a Single Manager for Conventional Ammunition production facility project for the U.S. Navy/U.S. Air Force Fuel Air Explosive (FAE II) program. Figure 1 illustrates the huge tailcone to be die cast for the FAE II 2000 lb BLU-96/B concussion bomb. The die casting demonstration will represent a significant state of the art advancement for the following reasons:

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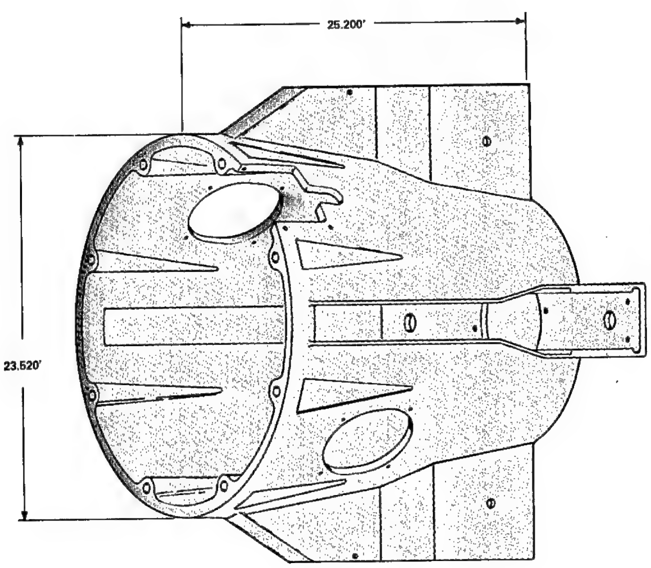

Figure 1

- Largest part ever to be die cast (over 13 square foot outer surface area and 72 lb weight).
- Gigantic die casting die (22 ft high, 6.5 ft deep, and 20 ft wide). The total die weight (cores, slides, base, inserts, ejector and cover halves) will weigh 117 tons. As an example of the die size, Figure 2 shows the cover half of the die being polished prior to the shipment to Doehler-Jarvis.
- The die will be mounted in the world's largest (3,000 ton) commercially available die casting press (Figure 3).
- An immense trim die (8½ ton) will remove the casting flash or scrap. The trim die will be 9 ft high, 11 ft deep and 7 ft wide.
- The technology developed has vast commercial application, such as in the manufacture of automotive engine blocks, transmission cases, and computer mainframes.

Huge Savings To Come

Although the die costs over $1,000,000, it will self amortize in only 3½ days of production. This is because the tailcone costs will be reduced from $1600 for a heavily machined sand casting to $160 for a die casting which requires very little machining. For a production run of 100,000 tailcones, the total savings would be over $144,000,000. In a forthcoming article, the overall die project will be reviewed.

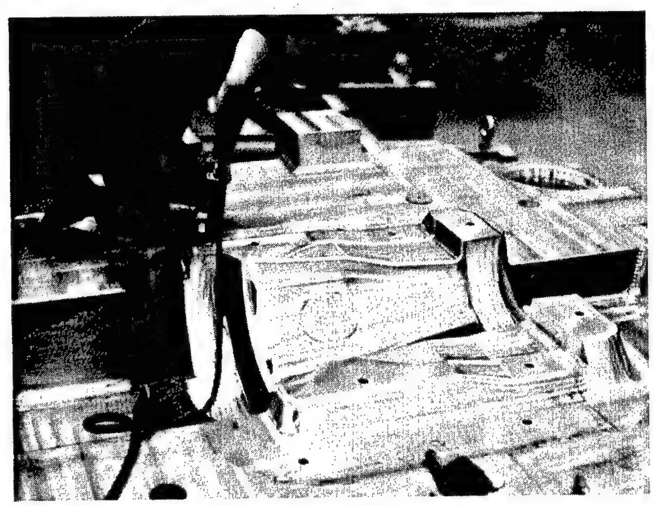

Figure 2

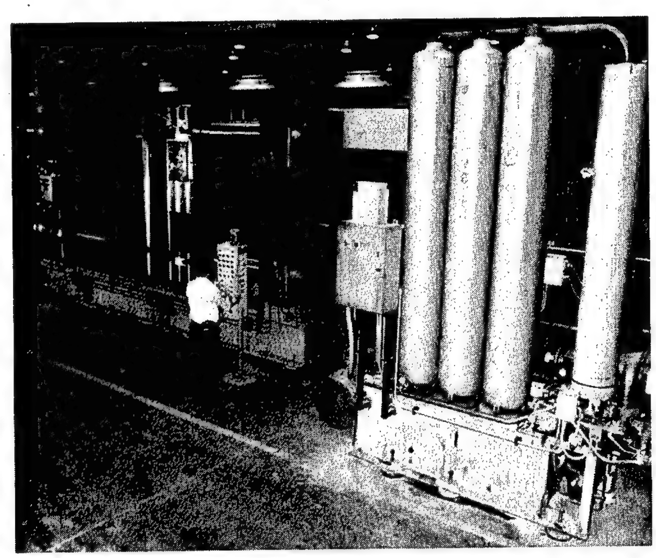

Figure 3

New Method for Cast Superalloy Frames

Segmented Mold and HIP Utilized

WILBUR H. SCHWEIKERT is Manager, Casting Projects, Material Process Development Laboratories, General Electric's Aircraft Engine Group. He is the inventor of the system for nucleation of high nickel and cobalt alloys for making fine grain castings to improve fatigue life. He also invented a system for making an inert mold for casting titanium and other highly reactive metals. For the past five years he has been involved in Air Force Direct Contracts relating to Hot Isostatic Pressing (HIP) of various alloys to improve the mechanical properties of the materials such as is reported in this article. Mr. Schweikert joined General Electric Company in 1951 to coordinate critical materials utilization on the J47 engine and also directed materials selection and process development for a new engine which eventually became the current J79 engine. He developed a procedure for making thin high strength stress free compressor discs and initiated isothermal heat treatment of engine wheels, blades, shafts, etc., in development engines. Mr. Schweikert initiated the process for coring precision cast air cooled turbine buckets and vanes in the years 1956 to 1960 and has worked with the casting industry to develop the system now capable of making the very sophisticated cooling systems in use in current engines. He received his Aeronautical Engineering degree from Yale in 1943, then flew in the European Theater during World War Two. He later received engineering degrees from Cincinnati University in Metallurgy (1948) and Mechanics (1952). He is a Registered Professional Engineer in California.

No Photo Available

PETER G. BAILEY is Manager, Forging and Forming, Manufacturing Technology Operation, Aircraft Engine Group, General Electric Company, Cincinnati, Ohio. Since joining the General Electric Company, Mr. Bailey has worked in the Process Development area for superalloys. In his previous position as Manager of Premium Casting Development, he had the responsibility for developing and evaluating advanced fabrication techniques for superalloys. He was responsible for process development in the densification of castings, including a prior Air Force direct contract, "Process for High Integrity Castings", a just completed Air Force contract, "Manufacturing Methods for Low Cost Turbine Engine Components of Cast Superalloys", and in-house applications of the densification process. In addition, he was responsible for development of ODS alloys and fabrication techniques. Mr. Bailey joined the General Electric Company in 1972. Prior to that time, he was involved in the development of dispersion strengthened mill products with E. I. DuPont deNemours and Co. and then Fansteel, Inc. Prior to his DuPont-Fansteel experience, Mr. Bailey worked for the Linde Division of Union Carbide Corporation, primarily in the application of industrial gases to steelmaking. At DuPont and Fansteel he was intimately involved in the manufacture, evaluation, and application of TD Nickel, TD Nickel Chromium, and TD Cobalt alloys. He was Principal Investigator on three Air Force sponsored programs. Mr. Bailey obtained a B.S. in Mechanical Engineering from Cornell University and an M.S. in Metallurgy from Stevens Institute of Technology. He is a member of the American Society for Metals.

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By combining the segmented mold process and a hot isostatic pressing (HIP) process, General Electric has developed an improved approach to the manufacture of aircraft engine frames and casings. The segmented mold process is effective in improving dimensional control

NOTE: This manufacturing technology project that was conducted by General Electric was funded by the U.S. Air Force Materials Laboratory. The AFML Project Engineer is Mr. Ken Kojola (513) 255-5151.

and surface quality in large structural castings. Additionally, the application of HIP densification has been shown to enhance mechanical properties and weld fabrication.

The segmented mold process was demonstrated in an Air Force supported General Electric project in which a 43 inch diameter fan frame was successfully cast at TRW in eight pieces (hubs, struts, and outer ring). Under conventional technology, the fan frames are manufactured by weld fabrication from many small castings and wrought subcomponents as shown in Figure 1.

The process involves producing the molds in pieces which divide the full mold into pie shaped segments. These segments are further divided into inside and outside panels. Figure 2 illustrates the concept with a two segment mold for a hub casting consisting of two inner panels, two outer panels, and cap pieces to hold the segments together at the top, bottom, and side joints.

Segmented Mold and HIP Utilized

Improved dimensional control is achieved as a result of several features of the segmented mold process. Metal chills are used in the wax patterns to improve pattern

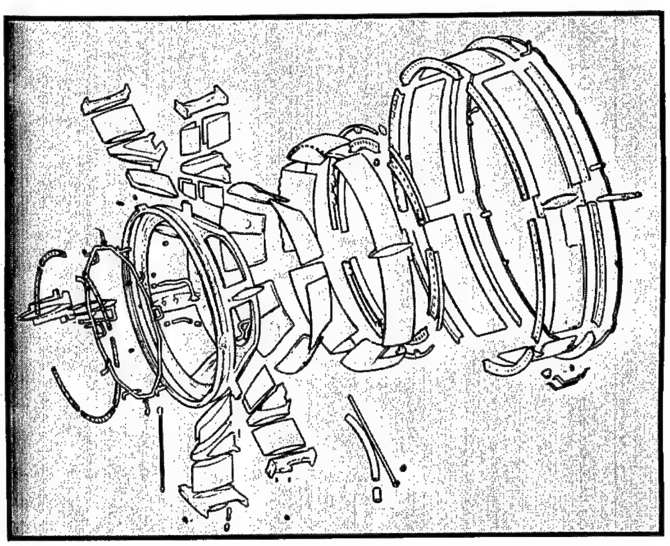


Figure 1

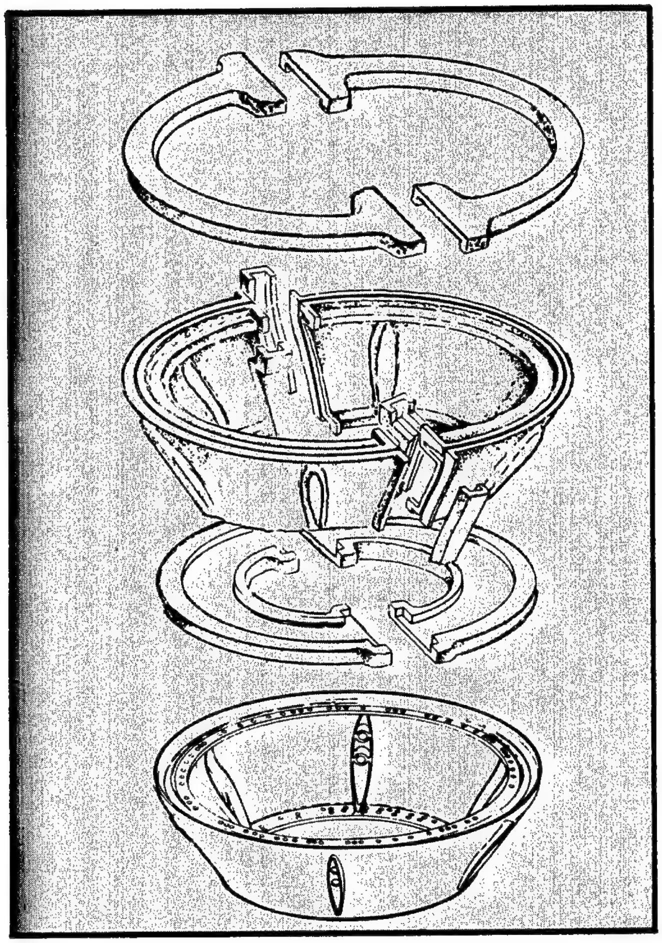


Figure 2

dimensional control after injection and during dipping, at which point they act as a dipping fixture. Being segmented, the mold allows for the removal of the metal chills during firing. Assembly fixtures allow for accurate and adjustable segment panel location. Figure 3 shows hub mold components ready for assembly.

The segments are assembled with the inside panels located to a predetermined diameter on the assembly fixture. The outer panels are then shimmed with sheet wax into proper position. Cores can be used with the segmented mold technique. More complex shapes—such

Figure 3

as integral fan frames—require that flange design be carefully considered. Cores may, however, be assembled with little difficulty in these geometries.

Optimum Pour Conditions Determined

Figure 4 shows the one-piece fan frame mold partially assembled on the assembly fixture. The hub segments are fully assembled and the inner panels of the outer ring are in place. The "horse collar" flanges for the strut mold attachments are visible. As shown in Figure 5, the

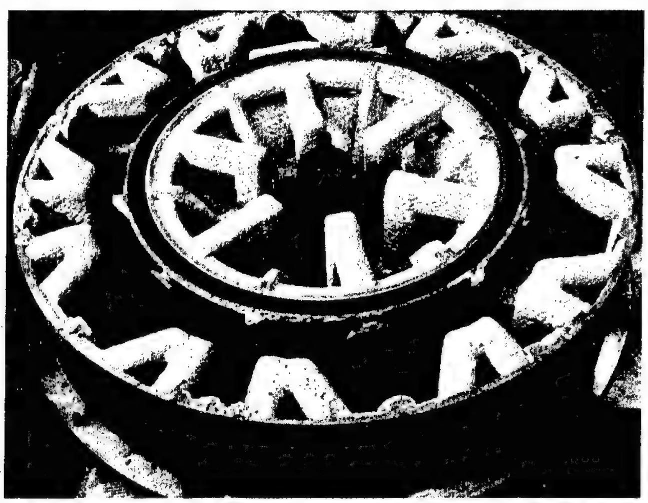


Figure 4

strut cores have been inserted through the outer ring inner panels into core prints in the hub mold. One strut panel is in place. The beginning of the placement of the outer panel can be seen in Figure 6.

Figure 5

The last of the one piece frame castings produced in the Air Force program was poured under the best conditions determined to date: metal temperature of 2930 F (1610 C), mold transfer time of 11 minutes, pour time of three seconds, pour weight of 500 lb (225 kg), and a vacuum of 15 microns.

Table 1 shows the typical excellent dimensional control achieved on the segmented mold castings. Significantly, the process allows for the repair of mold defects because of their accessibility.

Hub Castings				
	T.E., in.	Tolerance	L.E., in.	Tolerance
No. 1	14.353 14.341 14.347		21.150 21.145 21.133	
No. 2	14.304 14.326 14.377		21.084 21.112 21.135	
No.	14.368 14.395 14.340		21.115 21.137 21.096	
		± .0032 in./in.		± .0016 in./in.
Ring Castings				
No. 1	43.045 43.045 43.205		42.595 42.595 42.595	
No. 2	43.140 43.067 43.135		42.700 42.635 42.725	
		± .0019 in./in.		± .0015 in./in.

Table 1

HIP Densification/Homogenization

Although the closing of porosity can be effected at 2050 F or lower, higher temperatures are required for

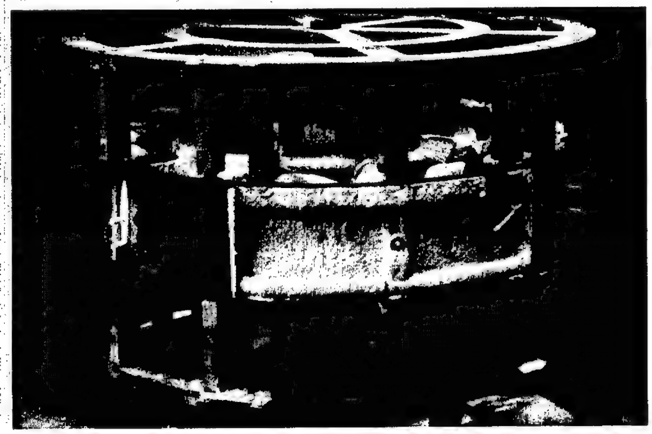


Figure 6

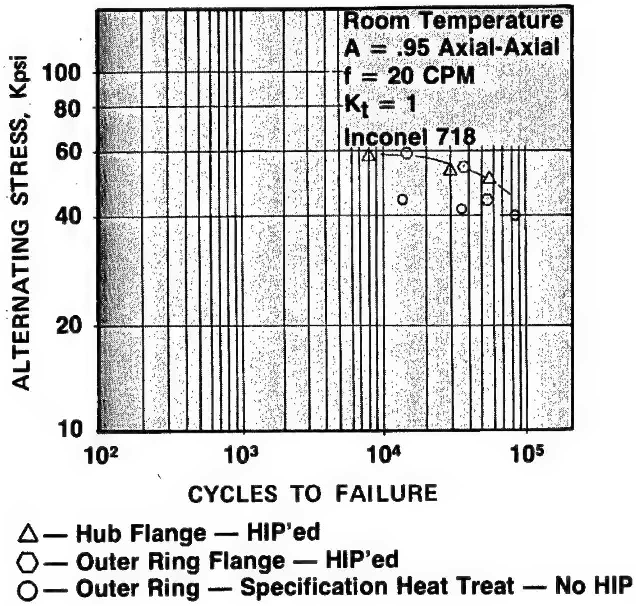


Figure 8

complete solutioning and homogenization. Electron microscope evaluation of the structures resulting from various thermal exposures and HIP cycles is shown in Figure 7. The left hand portion of Figure 7 depicts the typical structure of Inconel 718 homogenized at 2000 F. The lack of homogeneity and the large low melting Laves phase areas are detrimental to mechanical properties. The structure as shown in the center portion of Figure 7 shows what happens by HIP at 2050 F. The Laves phase is gone, but the orthorhombic Ni^3Cb needles have resisted solutioning. Complete solution of everything but the carbides is shown in the right hand portion of Figure 7. A uniform higher volume fraction of gamma prime, the strengthening phase, is evident. The best mechanical properties achieved were from material HIP'ed at 2125 F. This cycle eliminates the need for an additional solution treatment since it is included in the HIP cycle. Normal specification aging at 1325 F and 1150 F followed. Figure 8 shows the manner in which the HIP/heat treatment cycle improved low cycle fatigue life.

Prior to employing homogenization and densification in the manufacture of Inconel 718, as cast chemical milling produced a "Swiss cheese" effect due to porosity in the casting. In addition, chemical milling tended to attack grain boundaries in as cast material. Homogenization and densification have eliminated these problems. In fact, the process has improved the manufacturing of cast Inconel 718 to the extent that chemical milling for

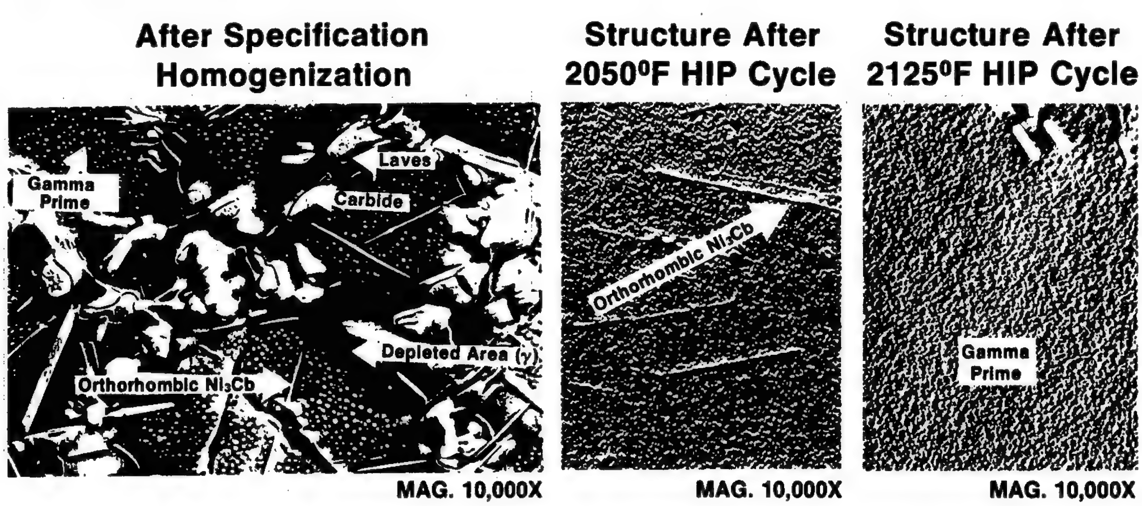


Figure 7

thickness reduction is now a feasible process. Figure 9 demonstrates the chemical milling panel experiments.

Machinability Improved By HIP

Weldability and machinability have also been improved by HIP, even to the extent that experienced machinists and welders have failed to recognize that the alloy was cast In 718. Fluorescent penetrant inspection (FPI) of a HIP processed 42 inch diameter F101 fan frame—weld fabricated from hub, outer ring, and struts after weld grinding—showed no cracks in the welds or adjacent cast material. After final aging, the FPI was repeated, again with no defects found. This freedom from weld defects is highly unusual for cast Inconel 718.

Other Applications Developed

To date, fan frames of the eight piece configuration have been cast and static load tested successfully. A number of significant applications for the segmented mold have been developed as a result of establishment of the process in the Air Force program. For example, a segmented mold low pressure turbine nozzle band casting has been manufactured in which the outer band features (which were previously end milled) were cast, thus saving considerable manufacturing cost. The casting was made deliberately undersize and was subsequently expanded to drawing requirement through the use of a Grotnes machine. This is only possible on material that has been HIP'ed.

Another spinoff application of the segmented mold process is its use on casting a low pressure turbine casing. As in other applications, diametral and wall thickness dimensional control were excellent.

Panel Selected For Chemical Milling After HIP

Chemical Milled Areas A, B, & C

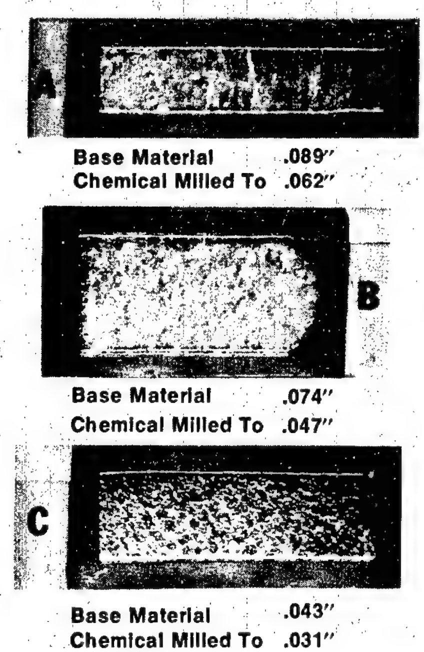


Figure 9

Over 40% Reduction in Titanium

Less Materials Used Via Isothermal Forging

From Paper By
Jerry D. Snow
and
Charles R. Cook
TRW, Cleveland

With titanium supplies critically short and prices very high, any process that conserves this important metal is welcome. A new blade manufacturing process developed at TRW should help. The hot die isothermal forging process could save 250,000 lb of titanium alloy between 1981 and 1986 on F-100 fan blades alone. Developed during a program for the Air Force Materials Laboratory, the process can provide better than 40 percent material savings and reduce manufacturing costs in comparison to current methods of fan and compressor blade manufacture. The program now has progressed through a large scale demonstration effort.

During this effort, TRW has first produced stage F-100 blades from Ti-8Al-1Mo-1V alloy that meet all metallurgical requirements. At present, these blades are machined from oversize forgings. As illustrated in Figure 1, this method requires 3.25 lb of alloy to produce 1 lb of final product. Using isothermal forging, the starting material requirement is reduced to just 1.83 lb.

Requirements Changing

Manufacturers have forged fan and compressor blades to near net shape for many years. However, blades on recent advanced aircraft engines are made from difficult to forge alloys and have very thin airfoils with less tolerance for thickness and geometric deviations. Fan blade design innovations that have contributed to the success of the F-100 engine, for example, include thinner airfoils, sharper edge radii, closer tolerances, and use of the high strength-to-density and modulus-to-density ratio Ti-8-1-1 alloy. Engine performance is outstanding, but manufacturing costs are high.

In the past, TRW has successfully used isothermal sizing for blade manufacture. In this process, a fully contoured but slightly oversized blade is brought to finished airfoil dimensional and surface finish requirements. This approach has proven cost effective by eliminating a significant amount of manually controlled finishing from the process sequence. Clearly, the next step in advancing isothermal forging technology was to attempt larger degrees of metal movement—in effect, to combine conventional press forging and isothermal sizing into a single isothermal forging operation.

Process Development

Development programs over the past several years have demonstrated the capability of isothermal forging to achieve substantial metal flow in titanium alloys using hot dies and low strain rates. In addition, work at IITRI identified IN-100, a highly alloyed nickel base material, as an acceptable die material for titanium forging. How-

NOTE: This manufacturing technology project that was conducted by TRW was funded by the U.S. Air Force Materials Lab, Wright-Patterson AFB. The AFML Project Engineer is Robert J. Ondercin 513 255-2413.

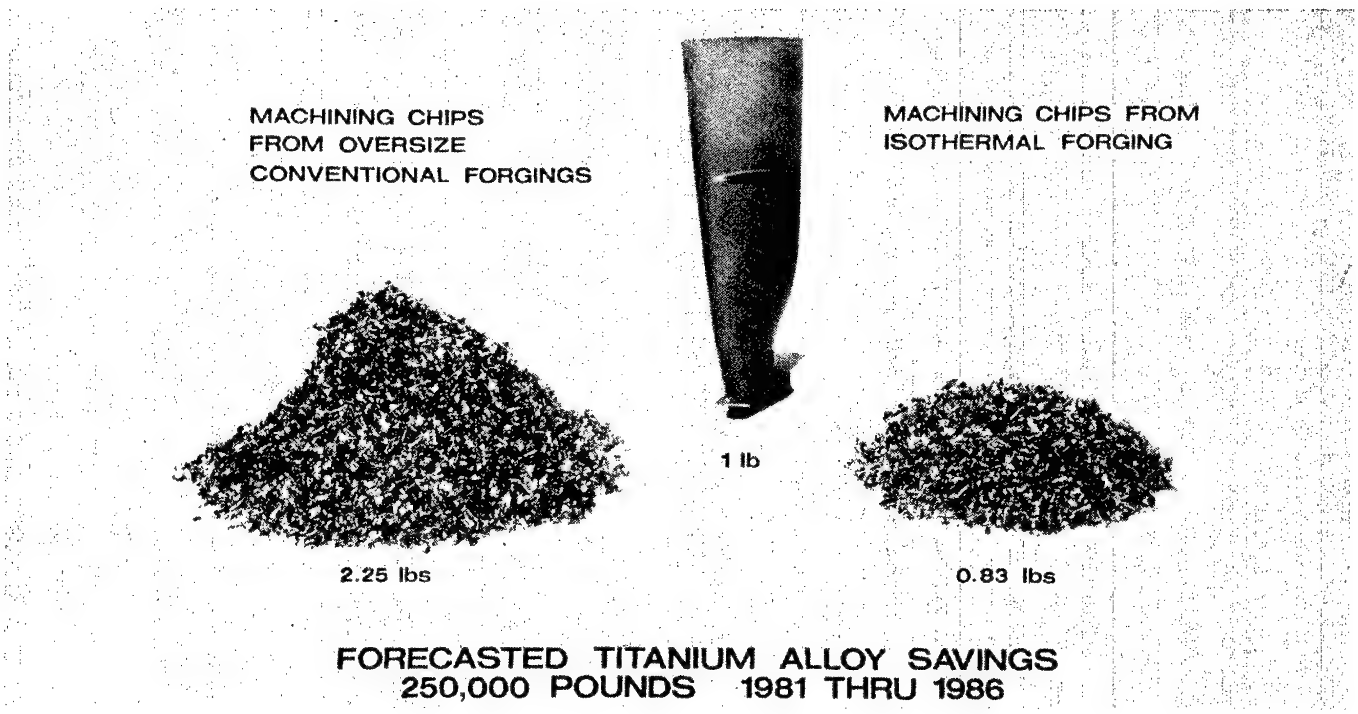


Figure 1

ever, there were many concerns regarding applicability to large scale production of fan blades. Some of these concerns (which have been answered positively during the development work) are manifested by the following questions:

- Can a surface finish acceptable for blades be obtained in precision forged titanium alloys?
- Will the IN-100 dies withstand the high temperatures and pressures required to forge Ti-8-1-1?
- Can finished blades be removed from the die without distortion?
- Will finished blades meet specified metallurgical characteristics?
- Will the dies be serviceable over long periods without deformation, distortion, or washout?
- Can die temperature uniformity be maintained under production conditions?
- Is the process economically viable?

Improved Lubricant

Perhaps the most significant program accomplishment was development of a forging lubrication system for use on hot dies. Earlier programs had used fused glass lubricants. These materials built up in die cavities, causing parts to stick in the die and factory surface finishes. TRW has developed several proprietary lubricant systems to overcome these problems.

The system used in the demonstration program on F-100 first stage blades consisted of a vitreous hydrodynamic component, a graphite boundary film component, and boron nitride, included primarily to promote separation of the part from the die. For this effort, the IN-100 dies were heated by electrical resistance cartridge heating elements placed through the width of the die blocks. The elements paralleled the airfoil chord and were about 5/8 inch below the surface. Six heating zones were serviced by independent power supplies in order to balance die heat input. In addition to the six control thermocouples, twelve thermocouples monitored die block temperature.

During forging, lubricant accumulation in die cavities was minimal. At one point, 202 consecutive forgings were made without cooling the die for cleaning. Acceptable surface condition was maintained by occasional wire brushing.

Preform Design

Blade preforms for the developmental effort were produced by conventional mechanical press forging procedures. A series of forging trials established the preferred preform configuration and mass distribution. The preforms exceeded finish thickness by approximately 0.060 inch on the airfoil surfaces and were 0.260 inch oversize on the root envelope.

Initially, blades were forged in a single isothermal squeeze to final net size. Although a few blades were successfully forged by this procedure, the process was judged as borderline for production purposes. Problems arose because the isothermal lubrication system was not adequate for the large amount of metal movement required. In order to ensure the delivery of quality blades, a two squeeze technique was adopted. In production, it would be preferable to conventionally forge the preforms to within 0.030 inch of final thickness. Starting with a thinner preform, a single isothermal squeeze should produce blades with net dimensions and acceptable surface finish.

Forging Conditions Established

TRW forged more than 300 blades using the double squeeze isothermal forging process. Forging temperature was maintained at 1760 F ± 20 F for most of these forgings. The forging cycle for the first squeeze is shown in Figure 2. Between the first and second squeeze, the blades were cleaned, given an acid treatment to remove any surface oxidation, and recoated with lubricant. The second squeeze was identical to the first except for a shorter dwell (1 minute) at peak pressure.

A major concern in this demonstration run was dimensional tolerances on the net forged platform surfaces, which are very tight for the F-100 fan blade. The forged tolerances obtained were not as tight as required. This was primarily because the die blocks tended to shift slightly sideways on each pressing cycle. The position of the die was corrected regularly after few forgings, but this situation nevertheless contributed to the standard deviation in relative platform positions. Different methods to secure the die blocks to the press bed are clearly

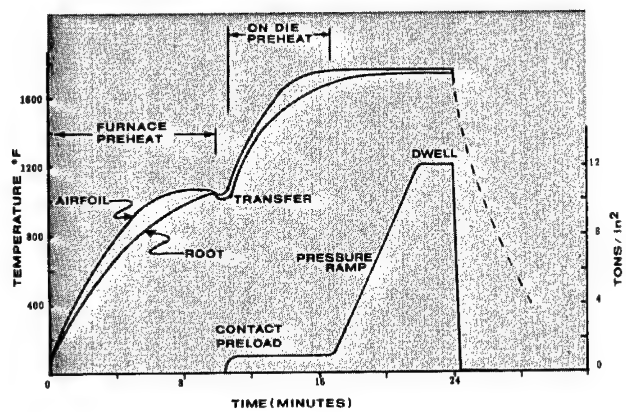


Figure 2

indicated and already are incorporated in the design of other isothermal blade forging die sets. With this sort of change, TRW is confident that isothermal forging can meet the close platform surface tolerances specified for F-100 fan blades.

Despite this shifting die block problem, 88 of the demonstration blades were within root shelf blueprint tolerances after root broaching, 30 blades were in some way oversized (these were all corrected by polishing), and 21 blades were undersized in some way (many of these were saved when the platform tapers were later machined).

Die Blocks Durable

The die blocks were inspected after 595 pressing operations and found to be still in good condition. No detectable changes in airfoil form had occurred. Some plastic deformation of the die was evident in localized regions, but because of the excess stock in the root, these regions were not detrimental. A slower rate of pressure buildup during the first isothermal squeeze or minor changes in the preform root design would be required to eliminate areas of localized stress.

Some fine cracks developed in the die surface early in the forging trials, probably originating from porosity in the castings. Although the cracks propagated slightly (to a maximum of 3/4 inch), they did not cause any defects of the forged blades. Apparently, such cracks fill with lubricant during forging, preventing any possible problems.

Mechanical Properties High

The capability of the process to produce metallurgically acceptable blades was another concern. The Ti-8-1-1 blades are solution and age heat treated after forging. Solution treatment is in vacuum at 1700 F for 1 hour followed by forced argon cooling. The aging cycle consists of 8 hours at 1050 F. Mechanical properties of the isothermally forged and heat treated blades were determined on specimens taken from the center portion of the airfoil between the root and midspan. As shown in Table 1, properties were well above specification. Blade microstructure also was entirely satisfactory.

Two alternative thermomechanical treatments were investigated. In the first, the blades were processed through the solution anneal heat treatment before rather than after isothermal forging. The second approach was to assume that the isothermal forging operation itself provided a solution anneal—i.e., the blades were aged only. Mechanical property data on these blades is also included in Table 1. Microstructures and mechanical properties of the blades that were solution annealed before isothermal forging were equivalent to those of the production lot blades. The aged only blades appeared to be significantly stronger but slightly less ductile than production lot blades and had similar microstructures. They did have slightly more transferred beta structure, which could account for the higher strengths.

	Tensile Properties								Stress Rupture Properties			
									150 KSI 75 F V-Notch Hours	57.5 KSI 1000 F Smooth Hours	% Elong.	% RA
	UTS, KSI		YS(0.2%), KSI		Elong. (%)		RA (%)					
Forging No.	75 F	800 F	75 F	800 F	75 F	800 F	75 F	800 F				
Production Lot 106	144.1	102.5	135.7	82.8	20.0	23.6	48.4	56.7	6.0-T	19.0-R	49.1	65.9
107	144.5	101.7	134.6	82.8	21.3	27.9	46.0	55.0	5.9-T	25.1-R	67.7	65.2
Development Lot Avg. of 3	140.2	99.4	131.1	79.9	22.9	22.3	48.1	64.3	5.2-T	30.1-R	46.1	70.4
Specification Minimum	130	90	120	70	10	10	20	25	5	15	7	—
Solutioned Before ItF Avg. of 2	146.6	102.9	137.7	84.2	18.8	22.5	42.7	56.0	15.8-T	30.8-R	43.7	64.7
Aged Only Avg. of 2	152.8	108.0	145.5	89.7	20.7	22.5	45.7	55.3	5.3-T	28.7-R	37.9	63.5

ItF = Isothermal Forging
T = Terminated
R = Ruptured

Table 1

Twist a Problem

When removed from the isothermal dies, the forged blades were excellent from a bow standpoint but were significantly undertwisted and well outside permissible angular tolerances, as seen in Figure 3. The undertwisted condition worsened when the blades were given a solution anneal heat treatment, as indicated by the lower curve in the figure. This behavior appeared to be reasonably reproducible, meaning it should be possible to design an extra increment of twist into the tooling to compensate for the tendency of the blade to unwind.

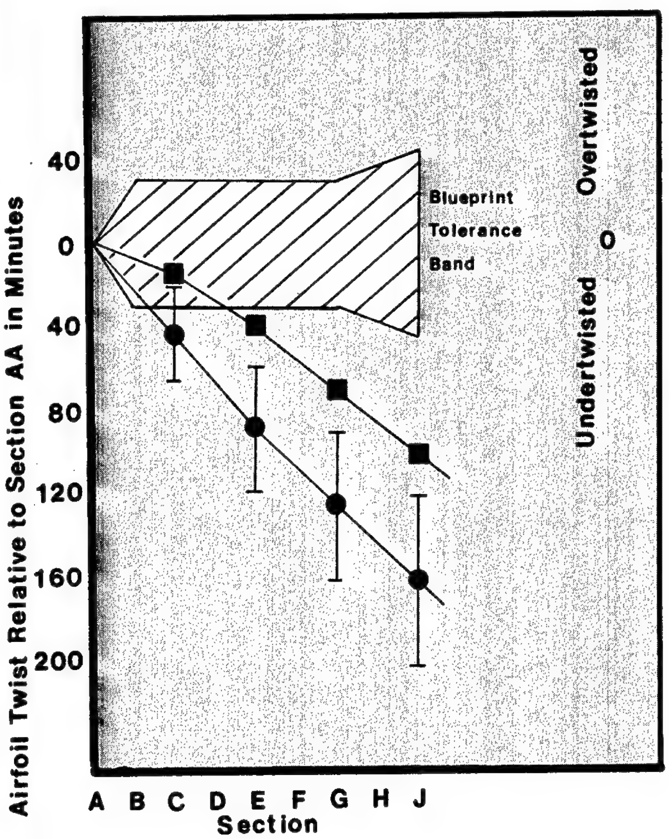


Figure 3

Because of the undertwisted condition of the blades, a warm straightening operation was added to the manufacturing process. Such operations are common practice in conventional fan blade manufacture. Straightening was carried at 1100 F in overtwisted tool steel dies.

Machining Problem Solved

One other problem was encountered and resolved in final machining. The blades were machined conventionally, with the root completely machined and the mid-span elements then rough machined. Before finish machining the close tolerance mid-span notch faces, fan blades are customarily given a stress relief heat treatment. When this procedure was followed with the isothermally forged F-100 blades, they unwound to an uncommon degree. This distortion forced more than half the blades outside tolerance specifications for airfoil twist and mid-span back contour. This degree of blade distortion could not be corrected using manual techniques; however, investigation of straightening alternatives was not required, either. Instead, the blades were given an intense glass bead peening, which is normally the last operation before shipment. The surface stresses introduced during the glass bead peening caused the airfoils to wind up to approximately the same degree they had unwound during stress relief. With the bulk of the blades now back within bow and twist tolerances, the remaining mid-span machining operations could be completed. A localized glass bead peening, restricted to the mid-span region, completed this stage of the processing.

Single Squeeze, No Anneal On Way

As a result of this program, isothermal forging procedures have been established for titanium blades with reproducibility of the process successfully demonstrated. Blades produced by this process met all the metallurgical requirements of Ti-8-1-1 forgings for the high performance F-100 engine. As noted, the process can reduce manufacturing costs, particularly for larger blades, through improved material utilization and manufacturing time savings. Further process refinements should make it possible to isothermally forge these blades in a single squeeze and eliminate the postforging solution anneal treatment. These changes will further extend the economic advantages of the process.

New Coating for Printed Boards

UV Cure Offers Benefits

ROBERT L. BROWN is a General Engineer at the U. S. Army Missile Command in Huntsville, Alabama. His current projects involve creative direction of contractor engineers on projects such as the fully additive manufacture of printed wiring boards (Hughes), ultraviolet curing of conformal coatings for PC boards (Hughes), product cleanliness techniques for PC boards (Martin-Marietta), laser scan testing of PC boards (Chrysler), rigidflex assemblies (McDonnell-Douglas), and insertion of nonaxial lead devices in locaserts (Martin-Marietta), a recent approved success. A Registered Professional Engineer in Alabama and holder of a B.S. in Metallurgy (1958) from Alabama University, Mr. Brown holds six patents and is author of fifteen technical briefs which NASA rates as equivalencies to patents. He was the first recipient of the NASA "Noteworthy Contribution" award in 1970 for his many contributions to their technical utilization program, and patented several inventions that were used in production. While employed by Chicago Bridge and Iron in 1948 he invented an early television X-ray imaging system, which was the first such system to reach broadcast resolution and was the basis of an X-ray television system built by Zenith Corp. and delivered to Marshall Space Flight Center in 1972. This system was used at Vanderbilt University as the best available nuclear medical imaging system and is still in use there as a television X-ray system. His most recent development of an X-ray imaging system is characterized by revolutionary increases in resolution and performance through use of fiber optic technology, in which 80-100% of the radiation is captured in the image and resolution is more than 20 lines per inch, with increases easily possible through use of finer fibers. Also while at Chicago Bridge and Iron he patented a method for brazing claddings on dissimilar metals which was widely used commercially for many years. A member of the International Society of Microelectronics, Mr. Brown worked as an aeronautical engineer during World War II at Birmingham and also worked as an engineer with the Birmingham Fabrication Company.

Newly developed conformal coating material for printed wiring boards and its related application techniques offer significant improvements in the manufacture of these parts. An ultraviolet cured plastic, the coating is easily applied by spray, and it meets applicable requirements of the military specification for electrical insulation of compounds (MIL-I-46058). Hughes Aircraft, which developed the coating process during an MM&T program sponsored by the U.S. Army Missile Command, also specified a high production rate, semiautomated coating facility.

Although there is no tangible reduction in material cost or labor with the new coating system, it offers important advantages in curing time and is easier to handle because there are no components to mix. Present conformal coating systems are very slow curing—requiring as much as 24 to 36 hours of oven time. This extended cure introduces a strong possibility of contamination during curing, while adding a built-in delay to the production schedule. Furthermore, the slow cure allows coating sag, which can lead to little or no coverage of sharp contours on the printed boards.

Also, present coatings are two part (or more) systems that require mixing. This adds another operation to the

NOTE: This manufacturing technology that was conducted by Hughes Aircraft was funded by the U.S. Army Missile Command under the overall direction of the U.S. Army Office of Manufacturing Technology, DARCOM. The MICOM Project Engineer is Mr. Bob Brown (205) 876-5742.

coating process and opens the door for mixing errors leading to unsatisfactory coatings. The one part UV cured coating requires no mixing and is initially cured in a few seconds. (An oven postcure for 25 minutes at 200 F ensures curing of areas that are shadowed or obscured from the UV light.) Elimination of mixing and the introduction of rapid cure decrease the amount of rework and scrap and enhance the possibility of high speed semiautomated production.

As do present coatings, the UV coating requires addition of a solvent thinner to lower its viscosity for spraying. Thus, the system can still be improved. Further advantages will accrue by developing a system that needs neither a solvent nor additional thermal cure.

One Material Fully Qualified

In selecting the coating, Hughes identified and screened 34 candidate materials from 11 different suppliers. Eventually, three coatings, applied by both spraying and dipping, were judged satisfactory for qualification testing (MIL-I-46058). Characteristics of the three are summarized in Table 1. Only the sprayed samples were tested, yielding the results summarized in Table 2. The Grace 9332 and De Soto 2353-7 coatings were judged failures since neither passed the thermal humidity aging or fungus tests. Consequently, six month shelf life tests for these two coatings were not completed.

The Hughson 3650-21 coating passed the humidity aging test, but showed a slight shade change. It was not clear, however, whether the coating or the board was responsible for this change. A subsequent retest including control samples showed that the shade change is in the coating but is not detrimental, since lettering under the coating remained clearly visible. The coatings showed no inversion, softening, chalking, blistering, tackiness, of lack of adhesion of liquefaction with aging. Two additional materials identified in the interim—Grace XRCP 432C and De Soto 2633-115-1—also passed this test. These materials appeared satisfactory in cure, flexibility, insulation resistance, and appearance tests and are considered potential candidates for full qualification testing. In the meantime, Hughson RD-3650-21 is the one material that has passed all test requirements and is considered satisfactory for conformal coating.

Spray Application Superior

Initially, dipping was evaluated as a coating application technique. The effort was soon redirected toward spraying, however, for several reasons:

- Dipping usually requires more equipment, results in more waste, and requires more cleanup.
- Spraying can be done under existing lighting since the coating material is in a container rather than an open tank.
- Implementing the spray process required only minor changes to existing Hughes equipment for coating PCBs.

As a result of the development effort, Hughes has written a process specification for spraying, curing, and testing the boards. For spraying, the material is thinned to about 175 centipoise using about 27 percent butyl acetate. Parts are degreased in trichloroethane and areas of the board not to be coated are masked. Spraying is done with a Brinks Model 26 spray gun and a 78S nozzle at 30 to 40 psi. The gun is held about 6 inches from the board in a vertical position. Coated boards are air dried for about 15 minutes before curing. The rear of the board is coated and cured first and the process is then repeated for the front.

For curing, Hughes evaluated both horizontal and vertical holding fixtures. The horizontal fixture proved more satisfactory because the coated surface is placed in the focal plane of the UV lamp. With the vertical fixture, the coating slumps to the lower end of the board and curing is not uniform. In the MM&T effort, boards were cured in an Interpress Corporation Model BP 720-1 SPL scan series curing oven, which was available at Hughes. Following UV cure, the board is thermally cured at 200 F for about 25 minutes.

High Production Rate Possible

Hughes has specified a production facility that can produce 750 typical coated PWBs per 8 hour shift. The specified facility contains a series of batch run automated and semiautomated processing machines. A fully automated system was rejected because of high implementation costs and possible losses caused by individual machine outage. The proposed work flow diagram for this facility is shown in Figure 1 and the facility layout is shown in Figure 2. Equipment for this layout would cost about $134,000.

A proposed improvement to this setup is development of a one step curing oven—i.e., combining UV and thermal cures. Addition of this equipment would reduce handling of the parts, production costs, and the chances of damage to the boards.

Activity	Coating Type					
	Hughson RD 3650-21	Hughson RD 3650-21	Grace 9332 (A+B) (New Cure)	Grace 9332 (A+B) (New Cure)	De Soto 2353-7 (+BP)	De Soto 2353-7 (+BP)
Application method	Dip	Spray	Dip	Spray	Dip	Spray
Cure						
Under resistors	Yes	Yes	Yes	Yes	Yes	Yes
Exposed surface	Yes	Yes	Yes	Yes	Yes	Yes
Insulation resistance, ohms						
Initial	$>1 \times 10^{16}$	$>1 \times 10^{16}$	$>1 \times 10^{16}$	$>1 \times 10^{16}$	$>1 \times 10^{16}$	$>1 \times 10^{16}$
1 hr after cycle*	1.3×10^{15}	1.4×10^{15}	7.8×10^{14}	7.3×10^{14}	1.5×10^{15}	$>4 \times 10^{15}$
24 hr after cycle*	1.6×10^{15}	3.0×10^{15}	2.4×10^{15}	1.9×10^{15}	2×10^{15}	2×10^{15}
Thickness, in.	0.002	0.001	0.002	0.002	0.003	0.002
Cure method	Horizontal; 2 scan + 200 F oven for 15 min	Horizontal; 2 scan + 200 F oven for 15 min	Horizontal; 2 scan + 200 F oven for 15 min	Horizontal; 2 scan + 200 F oven for 15 min	Horizontal; 2 scan + 200 F oven for 20 min	Horizontal; 2 scan + 200 F oven for 20 min
Appearance	Wavy; few small craters; clear	Very slight orange peel on back; clear	Smooth, clear	Smooth, clear	Wavy, clear	Smooth clear
Flex test	No cracks at bend	No cracks at bend	No cracks at bend	No cracks at bend	No cracks at bend	No cracks at bend
Comments	Has black light response; one part system	Has black light response; one part system	Has black light response; three part system**	Has black light response; three part system**	Black light response; two part system (add 5% BP to resin)	Black light response; two part system (add 5% BP to resin)

*Temperature-humidity tests run per MIL-STD 202 Method 106 10-day cycle. Exception: insulation resistance readings taken before (initial), 1 hour, and 24 hours after test.

**Three parts — Blend B is dissolved in acetone, then added to Blend A.

Table 1

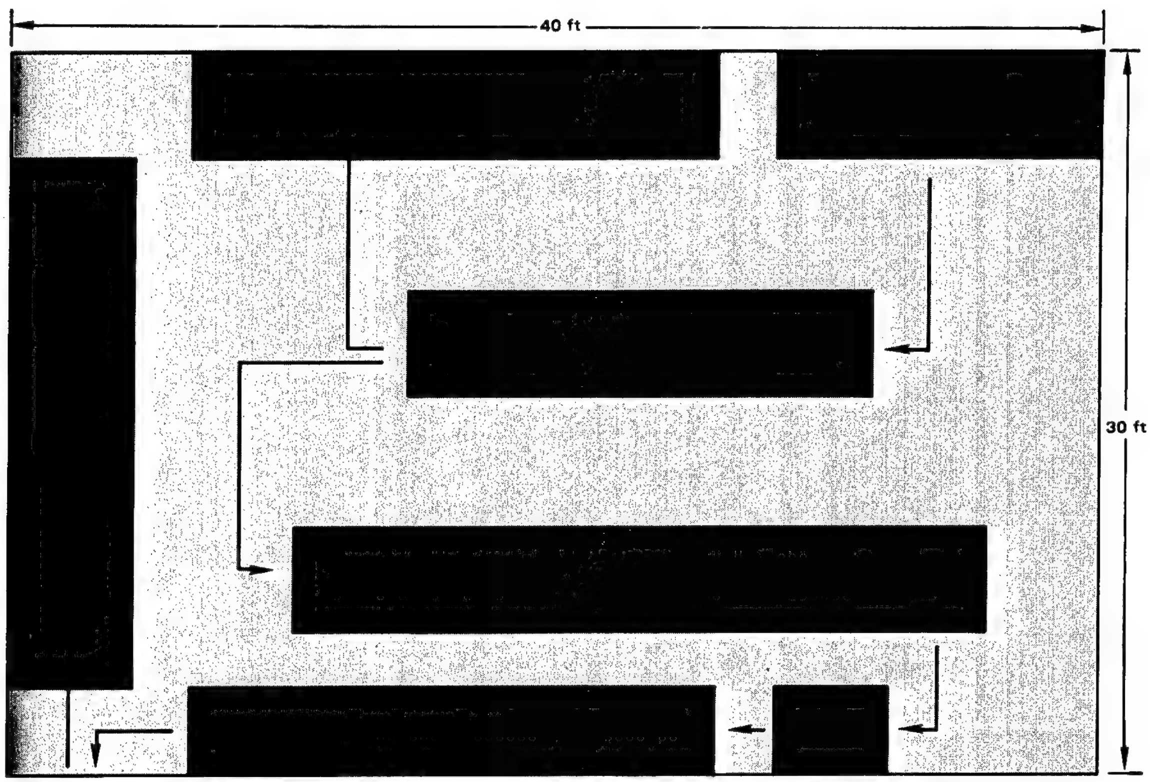


Figure 2

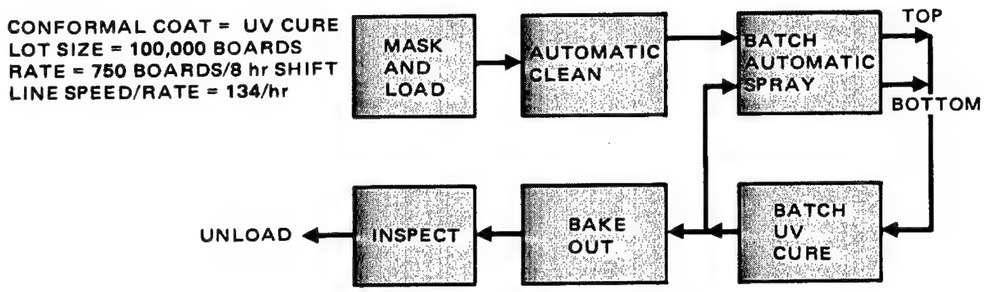


Figure 1

Examination or Test	Coating Specimen Test Results: Hughson RD 3650-21	Grace 9332 A/B	De Soto 2353-7 (+BP)
GROUP I			
Cure time and temperature	Interpress Scan Series 720-1 200 watt/inch mercury arc lamp, low intensity, scan speed 69 inch/minute, followed by 25 minute dwell in a 200 F air circulating oven		
Appearance	Passed	Passed	Passed
Coating thickness	Passed (0.001 in.)	Passed (0.001 in.)	Passed (0.001 in.)
Fungus resistance	Passed	Failed (growth noted after 28 days)	Failed (growth noted after 21 days)
GROUP II			
Shelf life			
Appearance	Passed	Not tested*	Not tested*
Insulation resistance	Passed (1.4 x 10^{15} ohm)	Not tested*	Not tested*
Dielectric withstanding voltage	Passed (0.77 μA)	Not tested*	Not tested*
GROUP III			
Q (resonance)			
Percent change in Q before and after coating			
1 MHz	10.1	26.7	55.6
50 MHz	18.4	7.6	4.9
100 MHz	9.1	27.3	1.8
Percent change in Q before and after 24 hr immersion in water			
1 MHz	16.3	40.8	31.7
50 MHz	5.9	37.0	35.5
100 MHz	5.9	3.9	1.1
Thermal shock			
Appearance	Passed	Passed	Passed
Dielectric withstanding voltage	Passed (0.50 μA)	Passed (0.51 μA)	Passed (0.49 μA)
GROUP IV			
Appearance	Passed	Passed	Passed
Insulation resistance	Passed (3.2 x 10^{15} ohm)	Passed (3.8 x 10^{15})	Passed (3.5 x 10^{15})
Moisture resistance			
Appearance	Passed	Passed	Passed
Insulation resistance (at 10 cycles) Average and minimum lowest value during cycles, ohms	2.6 x 10^{10} avg 1.6 x 10^{10} min	1.8 x 10^{9} avg 5.0 x 10^{8} min	7.6 x 10^{9} avg 5.9 x 10^{9} min
Dielectric withstanding voltage	Passed (0.68 μA)	Passed (0.79 μA)	Passed (0.76 μA)
GROUP V			
Flexibility	Passed	Passed	Passed
GROUP VI			
Thermal — humidity aging	Passed (slight shade change, resistor markings legible, no corrosion)	Failed (after 56 days: complete reversion, resistor alphanumeric markings illegible and missing, color change, severe metal corrosion)	Failed (after 56 days: coating fractured, resistor alphanumeric markings illegible and missing, metal corrosion, slight shade change)
GROUP VII			
Flame resistance	Passed	Passed	Passed

*Will not be tested since samples failed fungus resistance and thermal humidity aging, hydrolytic stability.

Table 2

Savings Up to 50%

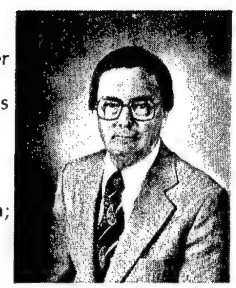
Superplastic Forming/Diffusion Bonding

Most savings of 50 percent and weight reductions of 40 percent are possible with a superplastic forming/diffusion bonding process developed by the North American Aircraft Division of Rockwell International. The work was sponsored by the U.S. Army Aviation Research and Development Command.

The process takes advantage of two unusual properties of the 6Al-4V titanium alloy—superplasticity and diffusion bondability—to produce structures of unprecedented complex configurations. The benefits are sizable in comparison with conventionally fabricated titanium components, and other significant production applications are emerging.

SPF/DB Fabrication Process

Shaping and joining are two fabrication processes fundamental to the manufacture of metallic structure. Limitations in the efficiency and cost effectiveness of these basic processes may seriously inhibit the use of an otherwise valuable structural material. Such has been the case with titanium in the aerospace industry. Superplastic forming/diffusion bonding (SPF/DB) is a new fabrication process which provides an attractive answer to this dilemma.



EDWARD D. WEISERT is Supervisor of Advanced Fabrication Technology, North American Aircraft Division, Rockwell International. In the last five years he has been responsible for developing the SPF/DB process into a viable production process. Mr. Weisert is a graduate of the University of Michigan with degrees in metallurgical and chemical engineering. Former affiliations include Technical Director, Special Metals Corporation; President, Isopressed Products Corporation; and Manager, Metals Research, Rocketdyne Division, Rockwell International. Mr. Weisert is a member of ASM, AIME, and AAAS, and has served on Material Advisory Board panels as well as national committees of both AIME and ASM.

NOTE: This manufacturing technology project that was conducted by North American Aircraft was funded by the U.S. Army Aviation Research and Development Command under the overall direction of the U.S. Army Office of Manufacturing Technology, DARCOM. The AVRADCOM Point of Contact is Gerald Gorline (314)263-1625.

The SPF/DB process takes advantage of elevated temperature characteristics inherent in the 6Al-4V titanium alloy. This alloy (perhaps uniquely) is endowed with a high degree of superplasticity and excellent characteristics for diffusion bonding. Thus, monolithic structures which combine severely formed configurations and joints of parent metal properties may be fabricated from titanium alloy sheet stock to achieve a new level of structural efficiency and cost effectiveness. First reduced to practice in December 1973, the general nature of this process is by now well documented and a wide variety of structural configurations have been demonstrated, as shown in Figure 1.

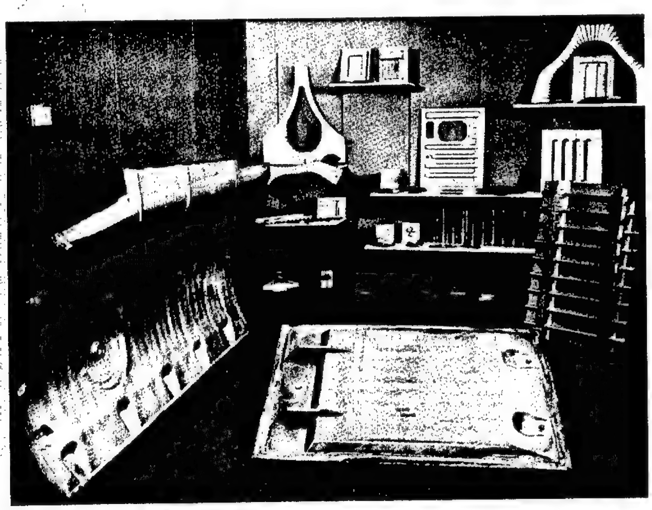


Figure 1

Superplasticity and Materials

Superplasticity is a phenomenon by which materials are able to achieve extraordinary elongations because they have inherently high resistance to neck growth. This occurs only within certain regimes of tensile deformation. The required conditions are elevated temperature and deformation rates within a discrete range. Optimum conditions are usually above half the absolute melting temperature and of strain rates within the second region of the log elevated temperature flow stress versus log strain rate curve. This region is characterized by a higher slope than that for the slower and faster strain rate regions of the curve. The slope reflects the strain rate sensitivity of the material being deformed. When plotted against the log strain rate, the 'm' value finds widespread use as a means of characterizing the degree of superplasticity in a material even though details of its exact nature and significance are still being pursued. Relative comparisons of strain rate sensitivity are very useful for optimizing the conditions for superplasticity. The 'm' value has been correlated with the degree of elongation achievable for a wide variety of materials. Thus, the 'm' versus log strain rate curve provides an indication of the range of strain rates associated with sufficient elongation to form a given configuration. In the practice of the SPF/DB process, this information is generally utilized to guide the rate at which to apply the forming gas pressure.

Incrementally increased cross-head speed testing is used to obtain the relationship of flow stress to strain rate at elevated temperature. Data bands for several commercial heats of the 6-4 alloy are available and may be utilized to guide superplastic forming without specific evaluation of the heat being formed. For especially demanding configurations—or for large components where the material/labor investment exposure is high—characterization of the individual heat(s) is indicated. It is anticipated that with production experience on a given configuration such precautions will be relaxed.

Materials exhibiting structural superplasticity are characteristically of fine grain size—typically less than 10 microns. The grain structure is also uniform, equiaxed, and resists grain growth at elevated temperatures, the latter usually by virtue of a two phase structure. With few exceptions, heats of the commercial 6-4 alloy have the requisite fine grain structure and exhibit a high degree of superplasticity in sheet form. Peak 'm' values at 927 C (1700 F) typically are 0.7 to 0.9, indicating available elongations of over 1,000 percent. Exceptions are rare, generally exhibiting banded structure or large amounts of blocky or acicular alpha, and these anomalies may be discriminated by metallography.

It has been recognized that desired fine grain structure for superplasticity is not stable during SPF/DB processing; rather, it is affected by both time at temperature and total strain. Grain growths from the as received, nominally 7-8 to as high as 20 micrometers as processed, have been observed. Usually, growth to 10 or 12 micrometers occurs, so the behavior has not precluded the

fabrication of a large variety of demonstration hardware. However, for optimum use of the process, it will be desirable to take in-process microstructural changes into account or even control them. As one step in the former direction, the in-process exposure to temperature of sheet stock prior to forming is being simulated in specimens prior to elevated temperature testing. To control grain growth, development of a 6-4 alloy grade containing small amounts of yttria has been suggested as a potential measure to control grain size.

The joining aspect of the process is similarly concerned with elevated temperature flow properties and fine grain size. In achieving intimate contact of two originally free surfaces, diffusion accounts for only a small, though vital, amount of the mass transport required, the majority being achieved by plastic deformation. Thus, the low flow stresses associated with fine grain size are desirable for bonding just as for superplastic forming. Again, in-process grain growth can adversely affect the diffusion bonding process and must be of special concern for bonds to be achieved late in the process cycle.

Alloys Investigated

SPF/DB fabrication technology to date has been demonstrated almost exclusively with the 6Al-4V titanium alloy. Elevated temperature data indicate that the 6Al-2Sn-4Zr-2Mo titanium alloy and to a lesser extent the 8Al-1Mo-1V titanium alloy should behave quite similarly in processing to that of the 6-4 alloy. A few demonstration specimens of hardware have been successfully fabricated from 6-2-4-2 alloy, and it appears that it could be utilized much the same as 6-4 alloy for applications where its superior elevated temperature strength is advantageous.

The 6-4 alloy requires a rapid water quench to develop maximum strength, which is incompatible with the complex SPF/DB configurations. Therefore, the 6-4 alloy is used essentially in a recrystallized annealed (RA) condition. While most aircraft applications are stiffness critical, there are cases where a higher yield strength is desirable. For this reason, a preliminary investigation of several beta alloys was performed. These alloys can be heat treated to high yield strengths in a quench/age cycle compatible with the complexly configured structure that is typical of SPF/DB processing. Also, they would offer lower processing temperatures than the 6Al-4V-Ti alloy. As shown in Figure 2, the alloys did exhibit significant superplastic behavior. Unfortunately, the 'm' values peak at relatively low strain rates, indicating long, probably excessive, processing times. Also, the diffusion bondability was shown to be very poor. It is interesting to note that all of these alloys had very large grain sizes—55 to 120 micrometer—which probably explains their poor bondability; but this is anomalous with respect to their distinct superplastic behavior. The explanation of the superplasticity put forth was the significantly higher bulk diffusion rates in the beta phase. This could provide the greater triple point accommodation required by large sliding grains.

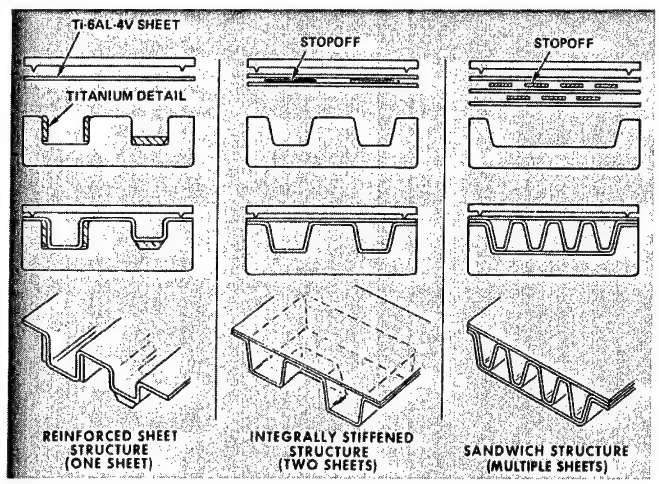


Figure 2

If the beta alloys are to be developed for SPF/DB, their processibility must be considerably improved. It is interesting to conjecture how beta alloys—with very fine grain size, perhaps stabilized by an inert dispersoid—might behave superplastically since the higher beta diffusivities would still be operable, yet distances associated with triple point accommodation would be greatly reduced.

SPF/DB Processing Features

The SPF/DB process as it emerged from Rockwell International's laboratories is simple on the surface. Ordinary MIL-T-9046 sheet is received, trimmed to size, and cleaned by standard methods. Fabrication may involve single or multiple sheets, as shown in Figure 3. In the case of the single sheet, it is entered into a stainless steel tool in which it is heated to process temperature 899 ±28 C (1650 ±50 F) while surrounded by argon, then forming and bonding are accomplished by use of argon gas pressure and the cleaning is followed by the application of a stopoff paint, usually by silk screen, which allows complex patterns of selective diffusion bonding to be applied. The sheets next are assembled into a pack, provided with appropriate plumbing for internal pressurization, and tack welded together. At this temperature the sheets are first bonded together, then formed. Behind this apparently easy process is the requirement for relatively sophisticated controls for all but the most primitive of configurations.

Features of this approach to SPF/DB processing include

- Gas pressure seals by tool pressure
- Diffusion bonds by uniform, isostatic pressure and/or tool pressure bonding
- Applicability to any number of sheets
- Complex or simple bond patterns accomplished in the same manner
- Sandwiches (three or more sheets) that can take various external form—e.g., stepped, tapered, curved, etc.
- Sandwich core sheet bonds that are self inspecting.

This process approach is being used by several companies in exploring the application of SPF/DB technology.

Alternate approaches to utilizing the superplastic forming and diffusion bonding characteristics have also been explored, notably by McDonnell-Douglas. Their system involves forming first then bonding, or doing this simultaneously. Bonding is accomplished by the pressure of a thin steel tool driven by the inflation of a pneumatic stainless steel bag or by autoclave pressure

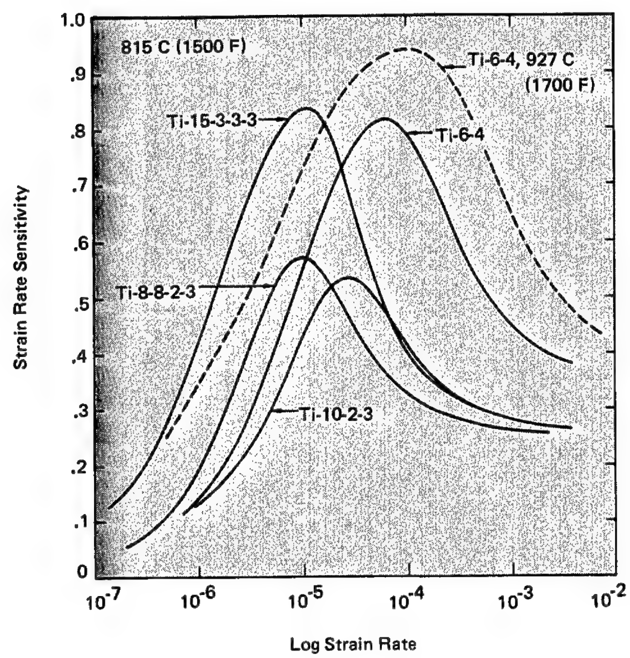


Figure 3

on a stainless steel envelope. This approach has the following characteristics:

- Uses edge welding to seal pack
- Avoids use of bond preventing stopoff
- Is limited to two sheet structure
- Avoids use of hydraulic press to close tool

Variety of Configurations Demonstrated

As indicated by Figure 1, a wide variety of configurations has been demonstrated by SPF/DB processing. In a recently completed AFML Manufacturing Technology Division program, three full scale B-1 bomber components were designed and successfully fabricated. These parts represent each of the three types of SPF/DB structure as shown in Figure 3, essentially one, two and three sheet technology.

A B-1 nacelle beam frame was redesigned for SPF/DB processing to represent the case of a single sheet formed and bonded to titanium details preplaced in the die. The frame, shown in Figure 4, is approximately 889 x 762 mm (35 x 30 in.) and incorporates reversed beading, a bonded center cap supported by the beading and flange reversal of 180 degrees within a short distance. Trade studies indicated that the SPF/DB frame would be 40 percent lighter and 43 percent less costly than the conventionally fabricated frame utilized in the fourth B-1 aircraft built. Fabrication of three frames was accomplished without difficulty. While the inner cap bond

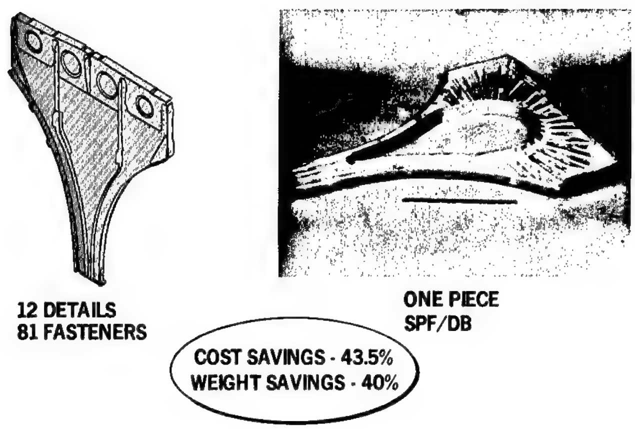


Figure 4

geometry did not lend itself to ultrasonic inspection, comprehensive destructive analysis of one of the frames indicated full bonding except near the final forming radius. The extent of bonding was considered well in excess of design requirements.

Two sheet technology was demonstrated by design and fabrication of an SPF/DB auxiliary power unit access door as shown in Figure 5. In this case, a hat section stiffened SPF/DB design was compared to a T section stiffened design which was machined from heavy plate for the first three B-1 aircraft. Trade studies indicated 31 percent weight and 50 percent cost savings for the SPF/DB design compared with the machined version. B-1 aircraft Number 4 had a door of this design but with the superplastically formed hat section fastened rather than bonded to the mold line sheet. This is because structure of this nature had not been subjected to acoustical fatigue testing at the time of the B-1 aircraft No. 4 design freeze. Subsequently, the third of a series of four doors fabricated was subjected to acoustic fatigue testing at levels well in excess of anticipated service conditions. The last five hours of a fifteen hour exposure were at 168 db. No damage could be detected in the exposed door using radiography, penetrant, and—more indicative—comparison of natural frequency responses and ultrasonic C-scans taken prior and subsequent to the fatigue environment exposure. The part was qualified for B-1 service.

The very first APU door fabricated during this program was produced without difficulty and was of good quality. Some minor grooving of the mold line sheet was corrected in subsequent runs by adjustment of the silk screened stopoff pattern registry. On the second run, however, severe defects were encountered which resulted from extrusion of the titanium pack into the tool cavity. On the third and fourth runs, doors of excellent quality were then produced by limiting the press pressure used to seal the working gas. At the time, the doors were the largest SPF/DB structure fabricated.

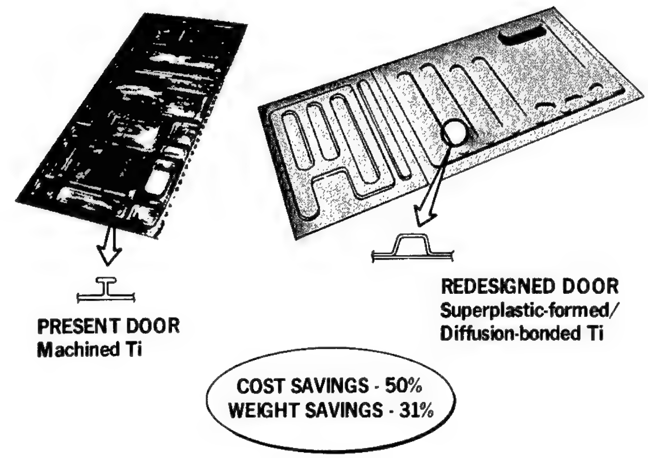


Figure 5

B-1 Engine Access Door Fabricated

To demonstrate three sheet SPF/DB sandwich processing, a lower engine access door for the B-1 was fabricated. The 279 cm (110 inch) long partially trimmed door is shown in Figure 6 prior to chemical milling and

Figure 6

final trimming. As fabricated, the door weighs about 113.6 kg (250 pounds). After chemical milling and final trimming the finished door will weigh about 35.6 kg (76 pounds). Most of this weight is lost through the milling of 2.29 mm (0.009 inch) face sheets down to levels of 0.36, 1.02, and 2.03 mm (0.014, 0.040, and 0.080 inch), with the predominant area being of the lightest gage. The design thicknesses are achieved by allowing the areas intended to be thinnest to form deepest into the mold

line tool. Upon chemical milling to a smooth mold line, the desired face sheet thickness distribution is achieved.

Panels, Lifting Fan Blades, Studied

Under Lockheed-NASA sponsorship, upper wing panels for the YF-12 were designed and fabricated as shown in Figure 7. Thirteen runs were made to deliver ten panels and provide inspection samples, probably the longest SPF/DB 'production like' run to date. One panel has been flying on the YF-12, while the balance are undergoing structural tests at Dryden Research Center. Tests accomplished to date all resulted in strength values significantly above design predictions.

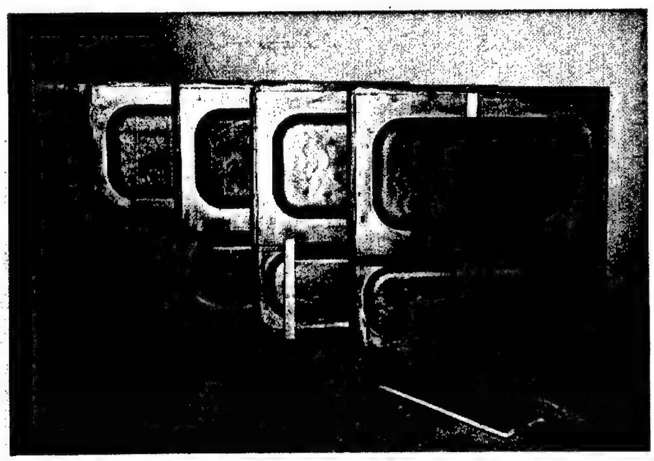


Figure 7

A recently completed AFFDL program demonstrated the feasibility of 360 degree SPF/DB truss core sandwich for use as a landing gear strut. Representing a six inch section of strut for the F-100 fighter, the cylinder, Figure 8, was the first demonstration of 360 degree SPF/DB technology. This has considerable significance for other applications, such as for helicopter engine components which are currently under study. One of these cylinders tested in compression failed at 158 percent of design load.

In work sponsored by Hamilton Standard, the potential of SPF/DB fabrication of V/STOL lifting fan blades was demonstrated by the spar specimen and the FOD sheath. (See Figures 9 and 10.) Considerable interest is being generated in rotating as well as static applications for propulsion.

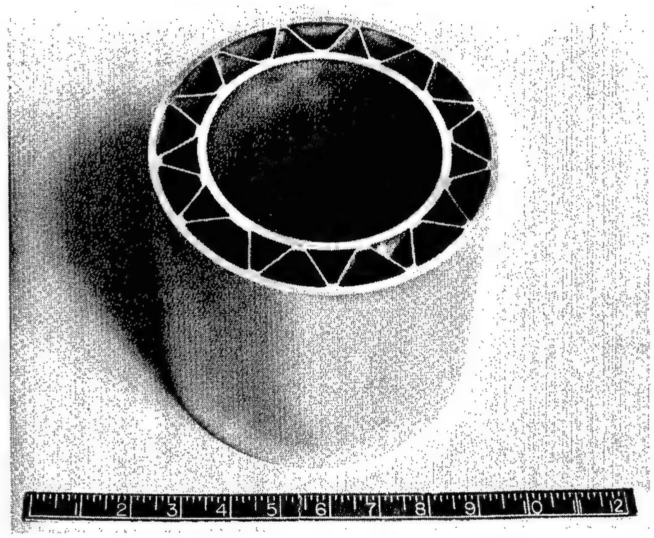


Figure 8

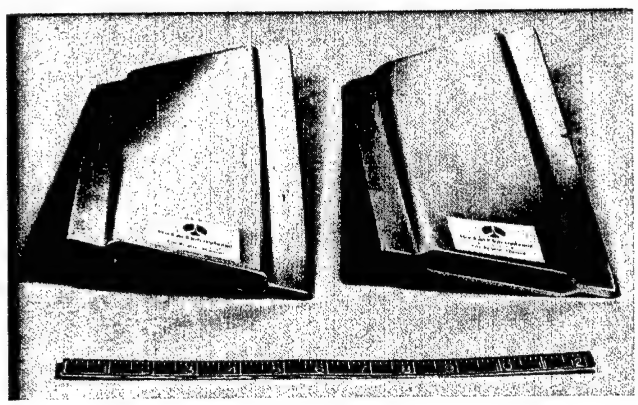


Figure 9

Figure 10

SPF/DB Versatility Shown

Demonstrations of SPF/DB hardware to date are notable by the diversity of configurations achieved. SPF/DB is an extremely versatile process and Table 1 lists current potential SPF/DB applications. Where titanium sheet must be used, SPF/DB processing is rapidly becoming a strong contending option. Studies also indicate that SPF/DB processing may be both weight and cost competitive for large aluminum structures such as for Missile X. Still another factor for considering SPF/DB application is the low life cycle cost associated with titanium, especially where corrosion and foreign object damage create high replacement rates. The attractive cost/weight advantages of SPF/DB are summarized in Table 2.

AIRFRAME	ENGINE	MISSILES AND SPACECRAFT	OTHER
Doors	Ducting	Primary Structure	Ship Decking
Fuselage	Cases	Doors	Heat Exchanges
Wings	Stator Vanes	Heat Shielding	Lifting Fan Blade
Stabilizers	Blading	Tanks	Laminar Flow Control
Shrouds	Flaps		
Fairings	Manifolds		
Ducting	Spinners		
Nozzles	Oil Tank		
Firewalls	Struts		
Bulkheads			
Landing Gear Struts			

Table 1

Pilot Plant Approach Useful

Is SPF/DB ready for production? The answer is a qualified 'yes'. To understand the qualifications, one must keep in mind two pronounced characteristics of the process:

(1) Unusual versatility in the configurations producible
(2) Strong dependence of process parameters on configuration.

In these respects, the SPF/DB process is much like precision investment casting. The fundamental approach is the same for all castings, but the procedural details for specific parts may vary considerably. Both generically new designs and distince variations of previously fabricated types often require initial developmental effort.

There now is a sufficient technical base to support production implementation for most of the generic configurations demonstrated if it is approached on a part by part basis with the assistance of the process developers. On the other hand, routine acceptance of engineering SPF/DB designs by manufacturing is probably a few years away. Training of production personnel to develop

Part Description	Percent: Cost Savings	Percent: Weight Savings
Nacelle center beam frame	55	33
Nacelle frame	43	40
APU door	55	31
Windshield blast nozzle	40	50
Precooler door	60	46

Table 2

an appreciation of the unique nature of the SPF/DB process will greatly facilitate transfer of the technology from research and development status. The SPF/DB process differs significantly from any other process on the production floor, including its basic components—superplastic forming and diffusion bonding. In addition, laboratory development of the process to its fullest potential should continue for some time so that updating and reorientation of production organizations will be of value on a continuing basis. Indeed, a pilot plant type of approach may be permanently associated with the production sources to handle the unprecedented or known to be difficult designs.

Automation a Certainty

SPF/DB processing is a natural for automation, and the development of techniques for SPF/DB using computer aided manufacturing (CAM) as well as design (CAD) may be predicted. The important SPF/DB process parameters are temperature, pressure, time, and atmosphere. Temperature has a large effect on the natural processes involved in SPF/DB and so, for the most part, the process is practiced isothermally. An optimum temperature is selected allowing a reasonable range of control for production activities—usually ± 28 C (± 50 F) for the 6-4 alloy. The future will probably see this range narrowed as superior heating techniques are developed. While current temperature control devices are satisfactory, their effectiveness could be improved by the monitoring capability of a CAM microcomputer.

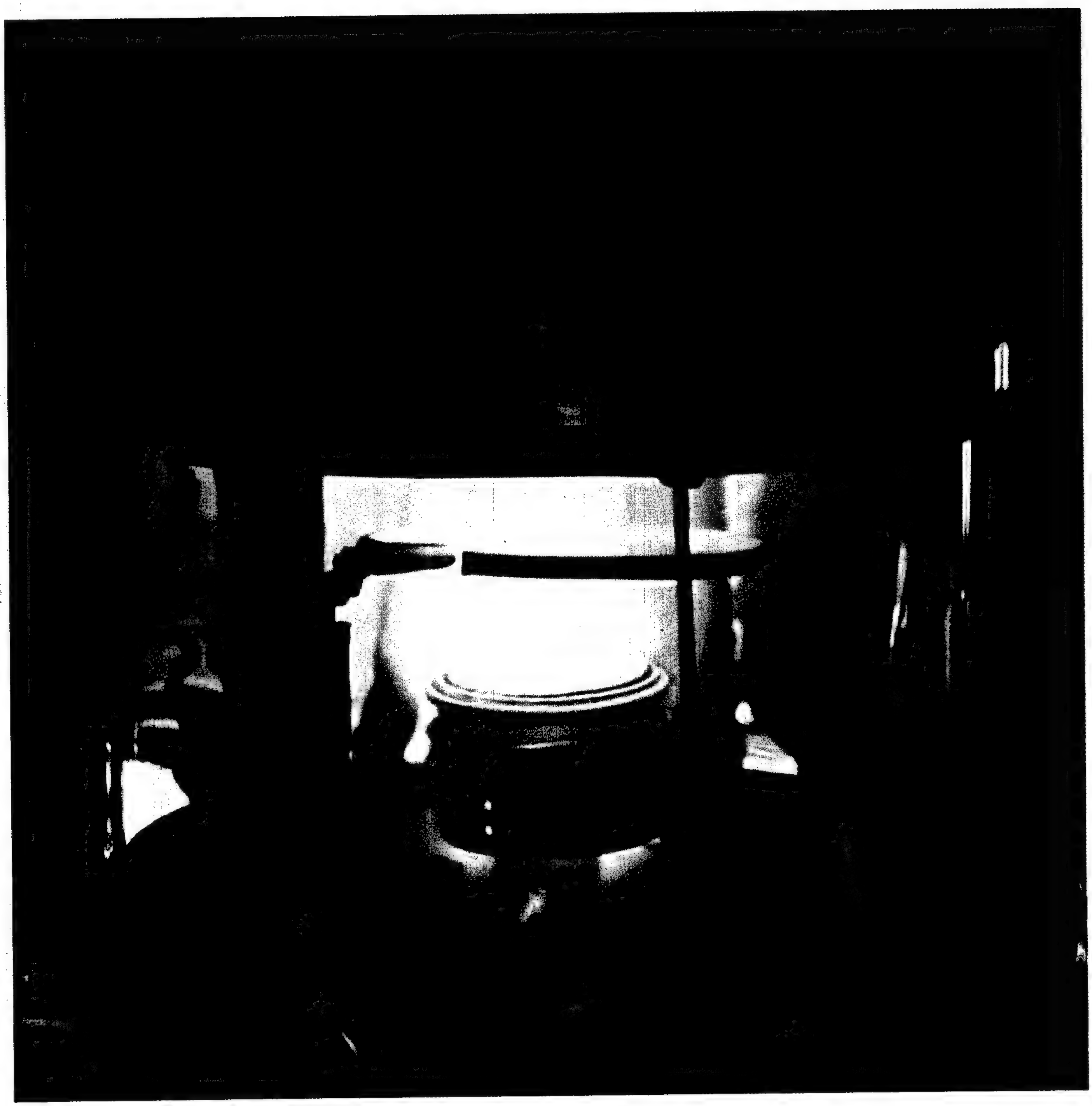
Currently, complex pressure-time curves are obtained by inputting design drawing and material property data into appropriate computer programs. The output is manually plotted into curves for the manual or automatic operation. These techniques will be adequate for initial production; eventually, CAM could take the raw data and control the process directly. With a central microprocessor monitoring and controlling the temperatures, pressurization, atmosphere, and material variations simultaneously for several production stations, the SPF/DB process truly may be as simple as it seems. It appears certain that SPF/DB will initiate a new era in titanium technology.

US Army

ManTech Journal

Building Reliable Systems

Volume 5/Number 4/1980



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ABOUT THE COVER:

The photograph on the cover of this issue shows the plasma polymerization coating deposition process in progress. Coatings deposited using this pollution-free process are typically hard, abrasion and chemical resistant, ageless, and watershedding. Clear, transparent coatings can be applied to wood, metal, glass, plastic, paper, and cloth. Recent research at Battelle's Columbus Laboratories has shown that the process can be scaled to production size at production acceptable deposition rates. Most recently, Battelle scientists have developed the capability to deposit these all-purpose coatings in color.

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Comments by the Editor

RAYMOND L. FARROW,

This issue of the U.S. Army ManTech Journal marks a significant milestone ending the year 1980. The coming issues in 1981 and subsequent years will feature a changed format from those 17 issues published to date in that they will contain considerably more useful information than before. Over twice the number of major articles will be presented in a more brief, concise style that will make it even easier for readers to learn of new developments in the Army's mantech programs.

In addition to this format with more numerous, but briefer, major articles, we will feature a section on brief status reports from all the Army commands, rather than concentrating on only one at a time or, as has been the case in recent issues, to not have a section on brief status reports at all. There also will be more notices of end of contract briefings and project demonstrations, along with a new section noting late breaking news items in the Army mantech program. These briefs and news items will be furnished the ManTech Journal by the U.S. Army Industrial Base Engineering Activity through its Newsletter office.

The changes forthcoming in future issues of the Army ManTech Journal are a result of the recent efforts of the Journal's Advisory Committee, which is made up of the technical consultants and advisors listed in the masthead on the inside of the front cover. The Committee recently met to consider several proposed changes in operating procedure for the publication, and the aforementioned items were partially the result of this discussion. The Editorial Staff feels that all the changes will be most beneficial to readers and that the magazine will contain much more useful information than ever before, representing a unique opportunity for readers to gain a comprehensive insight into 'what's happening' in the Army mantech program. Project developments from other services will continue to be reported; however, with the increased amount of information from within the Army's activities to be reported, emphasis will be on Army projects.

Readers are urged to comment on their reactions to these changes after receiving the first 1981 issue; they can do so by writing to the Editor at the U.S. Army Materials and Mechanics Research Center, Watertown, Massachusetts 02172. We will be most interested in your thoughts, and hope you will find the publication more valuable to your activities than ever.

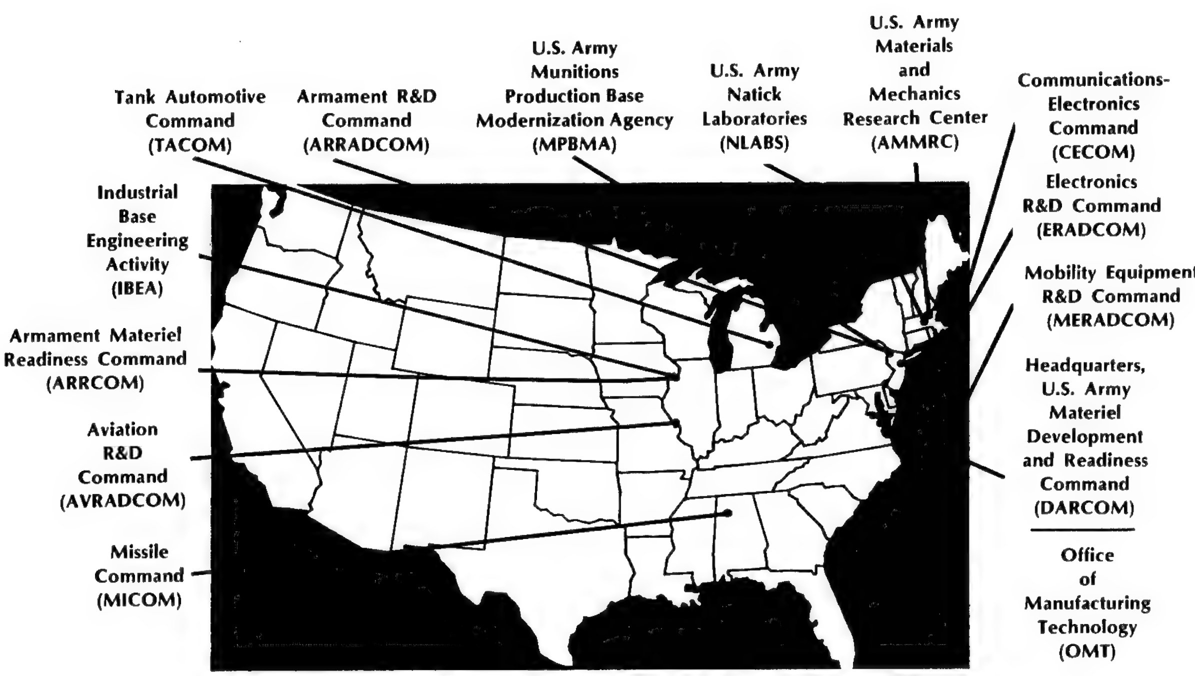
The articles in this last issue of 1980 contain several points of interest. The first three are related to the same items of military hardware and point up the fact that

any given mantech project can utilize several technological thrusts in the final design of the item. This often is the case, and this 'trilogy' of articles illustrates such a circumstance most clearly.

Other articles again reflect a wide spectrum of content, ranging from the problems encountered at the Army's munitions loading plants to electronics fabrication to how best to produce straight cannon tubes most efficiently. This wide range of topics is typical of the programs being conducted every day at Army facilities over the nation or by Army contractors from within the private sector. Such a wide range of subject matter mandates that a more voluminous coverage be initiated of these activities; that is one of the objectives to be achieved by going to the previously mentioned new format for the magazine.

The Advisory Committee is to be commended for its more active role in helping establish policies and operating guidelines for the Army ManTech Journal. This extra effort and interest on the part of these busy executives is much appreciated by the production staff. We realize how difficult additional time expenditure can be. We look forward to continued constructive suggestions toward making the Journal an even more viable publication. And we feel the reader will profit markedly from the upcoming changes.

DARCOM Manufacturing Methods and Technology Community



Could Save Over $100 Million

Hellfire Seeker Processes Improved

BOBBY C. PARK is a Chemist in the Manufacturing Technology Division of the Systems Engineering Directorate within the Missile Laboratory at the U.S. Army Missile Command, Redstone Arsenal, Alabama. Recently named Group Leader in the MT Division, Mr. Park received his A.B. Degree in Chemistry from Samford University. He was with Southern Research Institute for five years before joining MICOM 19 years ago. Author of over 15 technical papers, Mr. Park has been responsible for a steadily increasing number of projects in the Manufacturing Technology Division over the past several years.

Manufacturing improvements resulting from MM&T work on the HELLFIRE laser seeker (HLS) have led to an estimated 25 percent reduction in production costs. Discounted over a 5 year life cycle, total savings could amount to as much as $106 million; they could reach $87 million on the HELLFIRE alone, according to the U.S. Army Missile Command, sponsor of the program.

During the MM&T effort, engineers at Martin Marietta built on previously developed techniques and processes for the SMITHS seeker (see companion articles following in this issue) while utilizing COPPERHEAD subassemblies and components as much as possible. Existing processes, techniques, and parts were improved to reduce production time and costs and to upgrade seeker producibility without degrading system performance.

The MM&T effort concentrated on key high cost seeker items, such as the aspheric mirror, the detector/preamplifier, large scale integration (LSI) circuitry, and the gyro assembly. Integrating these improvements, Martin Marietta engineers have developed a cost effective plan for high rate production which they have already demonstrated on a pilot production line.

Benefits Other Programs

In addition to the appreciable HELLFIRE and COPPERHEAD savings, benefits of the improved manufacturing technology will extend to other defense systems. For example, both a diamond turning process for precision low cost mirror fabrication and improvements in LSI printed circuits have wider applications that could mean further cost savings.

In the course of the program, Martin Marietta developed process flow diagrams; process specifications; fabrication, assembly, and test tools; and manufacturing process plans that are now being used to fabricate seeker hardware. The techniques and processes developed were first validated by fabricating seeker components that were subsequently used to assemble 54 complete laser seeker sections. Tests at Martin Marietta verified that these sections met all necessary requirements.

NOTE: This manufacturing technology project that was conducted by Martin Marietta was funded by the U.S. Army Missile Command under the overall direction of the U.S. Army Office of Manufacturing Technology, DARCOM. The MICOM Point of Contact is Mr. Bobby Austin (205)876-8445.

Seeker Self Contained

The HLS is a low cost, semiactive laser seeker, shown in Figure 1, that is used on the HELLFIRE modular missile system. Mounted on the front of the missiles, it is 13 inches long and 7 inches in diameter. It comprises two separable units—the seeker head assembly and the electronic assembly. All parts are self contained with the exception of the primary dc power, which is provided by the parent missile.

The seeker dome, or optical window, protects the internal components, yet allows passage of target reflected energy to the detector/preamplifier subassembly. That assembly generates error signals indicating the angular error between the target and the detector line of sight. It also contains the immersion lens and optical filter. The gyro optics assembly provides a stabilized optical line of sight relative to the detector plane and moves freely with respect to the missile longitudinal (roll) axis. It includes the spinning optical mirror, support for the detector, and a means to drive and position the mirror/detector relative to the missile axis. The electronics assembly provides the means to spin the optical mirror and position the detector.

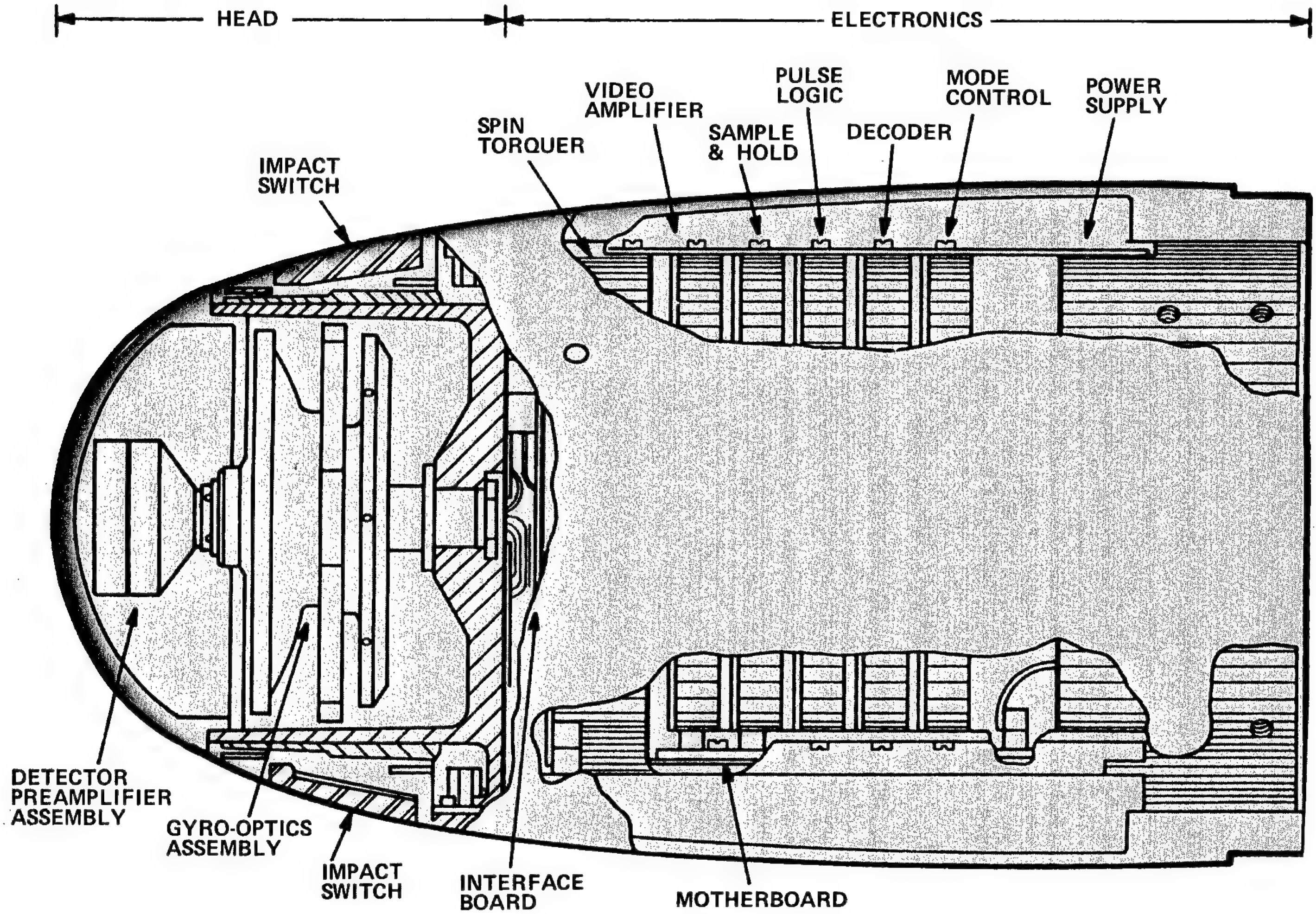


Figure 1

Processing Evaluated

There were basically three phases in Martin Marietta's MM&T effort to improve seeker manufacturing processes. During Phase I, they analyzed SMITHS and COPPERHEAD electronics designs to evaluate potential improvements in the production processes and techniques associated with proportional seekers utilizing a defocused spot detection system. Emphasis was on optimizing production processes and techniques.

Procedures for positioning the detector in relation to the optical system were evaluated considering linearity, instantaneous field of view, and cross coupling requirements. Process improvements involved modification of the detector support system, an improved seeker section substrate, and adoption of a single piece mirror and gimbal housing assembly. Test requirements for all elements of the optical system were considered to ensure desired performance.

EMI Control Stressed

Fabrication procedures were developed to ensure that electromagnetic interference (EMI) control is maintained on ultrasensitive circuits. Metal gyro assembly parts were evaluated but rejected because of weight and cost increases that overrode any improvements in attenuation. Knitted wire mesh fabric was chosen as the best dome shielding material, taking into account fabrication procedures. For connecting cross gimbal leads, twisted conductors with the tightest possible layup provided the optimum technique, considering both ease of fabrication and circuit insulation. Optimal procedures were also developed for bonding both within the electronics assembly and at the interface between the HLS and the missile frame. Lossy line filters were incorporated between the detector and preamplifier for maximum EMI protection.

Alignment procedures for gimbal angle and shaft rotation commutator pickoffs were another area of concern. Optical pickoffs for shaft speed rotation were found to be clearly superior to saturable reactors in terms of waveform purity, induced EMI, and circuit simplicity. Gimbal potentiometers were utilized because they are more cost effective and significantly improve gyro restraint performance.

Manufacturing techniques were developed to rapidly purge and seal gyro housings. For this application, COPPERHEAD pumping methods were modified to assure positive pressure inside the gyro.

Fabrication and registration techniques for producing optical patterns on complex gyro parts provided a final area of concentration during the Phase I effort. A decal on silver photosensitive alumina foil was selected because of the limited space available, the simplicity of the approach, and the low cost of decals in comparison to direct application of the pattern to the rotor hub or inside surface of the rotor by mechanical attachment, acid etching, anodizing or silk screening.

Analysis Continued

During Phase II, this process analysis was continued by:

- Evaluating quality control of the adhesive bonding used to provide bearing preloads and instituting low cost fabrication techniques for gyro gimbal assemblies.
- Investigating flexible tooling and procedures for accommodating various configurations of flex harnesses. Such procedures were found to be neither practical nor cost effective since primary tooling registration holes cannot be located for common pinning.
- Investigating procedures for sharing common printed circuit board assembly lines for high G and low G seekers, both of which require the same electronic circuit. (The high G circuit requires special testing.) As a result, common automatic component insertion equipment is used for HLS and COPPERHEAD production.

To validate the techniques and processes developed during Phase I and the first portion of Phase II, prototype components were fabricated and assembled into laser seeker sections, which were tested for conformance to requirements.

Pilot Production Line

The final task in Phase II involved analyzing the processes, techniques, and validation tests developed

during Phases I and II to determine the optimum procedures for pilot production. This included a plan to demonstrate a capability of producing 25 seekers per month.

During Phase III, Martin Marietta operated the pilot production line to determine process repeatability and establish process effects on rejection and rework rates, reliability, and costs. Process revisions were recommended, approved, and incorporated where applicable. Martin Marietta also identified any production line changes needed to produce a minimum of 175 seekers per month and also a minimum of 500 per month.

Molding, Machining Problems Overcome

During pilot production line operation, several key process problem areas were identified and corrected. One of these related to detector support manufacture. This part provides mechanical support for the detector/preamplifier and the optical filter and is also a lens in the optical system. It is injection molded from clear polycarbonate and machined to final dimensions. The detector support is shown in Figure 2. As molded, the spherical optical surface, A, is complete and requires no polishing. Surfaces B, C, and J were initially machined and surface C was optically polished. Hole E was drilled and milled and Holes F, G, and H drilled.

One problem encountered with this part was the extremely low yield of the injection molding process. The machine had to operate for several hours before achieving a stable cycle and producing consistent parts. In some instances, a production cycle was not reached in a normal shift and the machine was shut down to start all over the next day. To negate this problem, injection molding production runs were set up on a continuous (24 hour) schedule. Once the machine reached a stable cycle, the run was continued until the production lot was completed. This approach also produced more even quality distribution in the parts.

A second problem with the detector support was that holes F, G, and H in the neck were difficult to machine with conventional tooling and the parts tended to crack. Production yield of good parts ran as low as 20 percent. From a process review, engineers determined that the fixturing was adequate, but the tools and process were not optimized for drilling polycarbonate. Thus, the following changes were instituted:

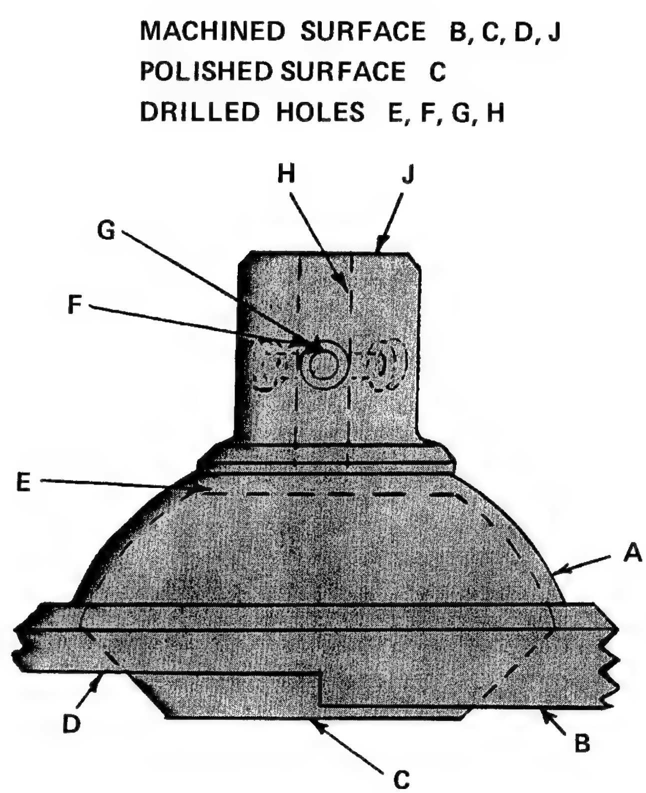


Figure 2

- Holes G and H were drilled and reamed to final dimension. Carbide tools were specified to minimize tool wear. Drills with a 90 degree point angle and drills and reamers with 10 degree or greater relief angles were specified.
- Hole F was machined with a carbide counter bore with a 10 degree or greater relief angle.
- The parts were flooded with coolant during machining, with the coolant flushed clear immediately afterward.

As a result of this process change, manufacturing yields greater than 90 percent have been experienced, substantially increasing producibility.

Laser Fixture Aligns Bearings

A second problem area during pilot production involved spin bearing installation. Initially, the gyro spin bearing set was simply inserted into a precision bore, relying on mechanical tolerances to align the mirror to the spin axis. This was not a reliable approach because, in some cases, the tolerance stackup would result in sufficient misalignment to cause excessive system guidance noise. The fact that some bearings could be installed at a slight angle further complicated the problem. To resolve this problem, bearings are now aligned and bonded in position using a precision laser aided alignment fixture. The switch to this fixture did not require a design change and had minimal impact on manufacturing costs.

The laser aided fixture precisely aligns the bearing set within the bearing bore. To do this, a laser beam is reflected off the mirror surface and onto a display panel. Runout of the mirror relative to the spin axis is observed as the mirror rotates on a runout requirement grid pattern. Adjustment is made by mechanically tilting or aligning the mirror within the fixture. When the mirror is properly aligned, a structure adhesive is injected between the bearing bore and bearing outer diameter. The fixture holds the system in alignment while the adhesive cures.

This process change insures repeatable precise bearing installation that allows the part to meet system guidance noise requirements. It also reduces labor hours by eliminating much rework.

Decal Alignment Difficult

A third problem area in pilot production was decal alignment. Initally, the decal pattern was aligned to the magnet poles after the magnet was permanently attached to the mirror. A fixturing arrangement was used to mechanically align the decal pattern to a mark on the magnet pole. The decal wafer was then bonded to the mirror frame. This process was not reliable because the pole mark did not insure proper location of the magnetic poles within the required tolerance band. The tolerance band that could be achieved by visually aligning the pole mark and the pattern mark added to the unpredictable results.

The problem was resolved by essentially reversing the process and aligning the system by instrumentation. The decal is now permanently attached to the mirror frame ahead of the magnet. The magnet then is aligned to the decal pattern electrically on the cross coupling test set. A fixturing arrangement provides a means of accurately marking the position of the magnet so that disassembly and reassembly can be achieved without losing alignment. The magnet is then permanently attached to the mirror frame.

Immersion Coupling Upgraded

The final problem area in pilot production related to an immersion process used to couple the detector surface to the optically clear polycarbonate detector support. The immersion fluid is a clear room temperature vulcanizing adhesive. Since the interface is part of an optical path, it must be clear of bubbles and separations. When the initial procedure established for this process produced unreliable results, Martin Marietta experimented with various modifications and was able to

- Revise the cleaning and priming procedure to ensure optimum adherence
- Revise the mechanical assembly technique to minimize bubbles and voids
- Eliminate several unnecessary process steps.

These changes resulted in a repeatable immersion process and reduced labor costs.

Mirror Process Unreliable

Throughout the MM&T effort, Martin Marietta was pursuing design and processing development for two key items in the assembly—the mirror and the detector/preamplifier.

In the early development phase of the HLS program, the aspheric mirror rotor was identified as a critical item. It was not possible to reliably manufacture the mirror on the gyro rotor substrate. This problem was reflected in the high unit cost.

A section of the prototype rotor is shown in Figure 3. The initial mirror blanks were produced by machining the aluminum substrate to undersize dimensions, plating the blank up to size by an electroless nickel process, and black chrome plating nonoptical areas. The optical surface was finished by precision machining with a single crystal diamond tool on an N/C lathe with 0.000001 inch incremental control. Despite the accuracy of the lathe, polishing was required to remove residual machining marks. These initial parts showed

- Marked deviation from optical surface from requirements
- Poor axial symmetry
- Irregular circular scratch marks caused by chips that lodged between the tool and the mirror surface during machining
- Severe misalignment between the gyro bearing axis and the rotor optical axis.

Furthermore, the process was unreliable and manufacturing costs were excessive for aspherical surfaces. This problem was not encountered on flat surfaces.

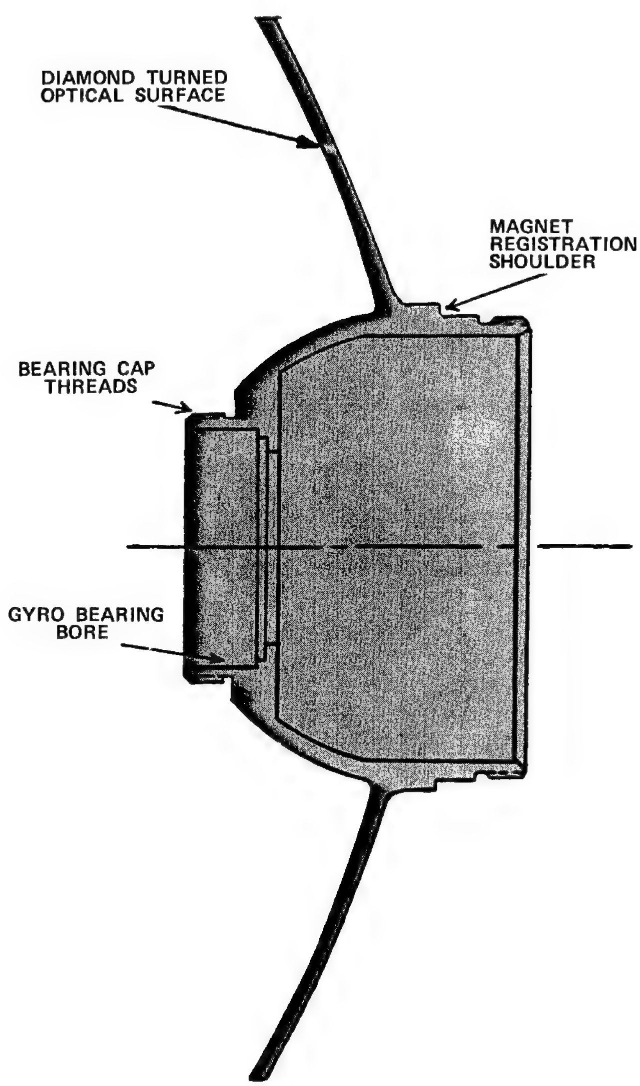


Figure 3

Stiffening Rim Helps

Since the structure was too fragile, a stiffening rim was designed for the outer edge of the mirror surface, as shown in Figure 4. This resulted in

- Improved optical surface accuracy
- More accurate axial symmetry
- Reduced circular scratch marks
- Greater process reliability.

The severe misalignment between the gyro axis and the optical axis was reduced by final machining the bearing bore in the same setup as the optical surface. In addition, bearing tolerances dictated a final alignment of the bearing axis with the optical axis. The bearings were then bonded in place as the last step in rotor assembly fabrication. The accelerated effort to achieve these improvements resulted in a producible aspheric rotor that cost about 40 percent less.

However, the cost was still too high, and a limited MM&T effort was carried out to assess the potential of electroformed surfaces for optical electroformed applications in laser seekers. But, since the optical quality was not adequate and the prospects for other fabrication techniques were extremely promising, this effort was dropped.

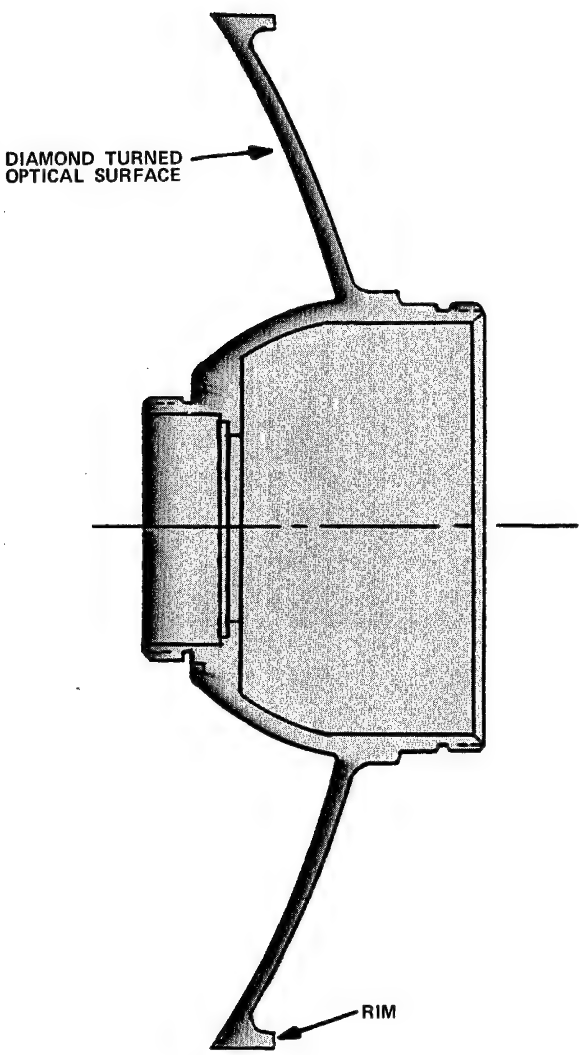


Figure 4

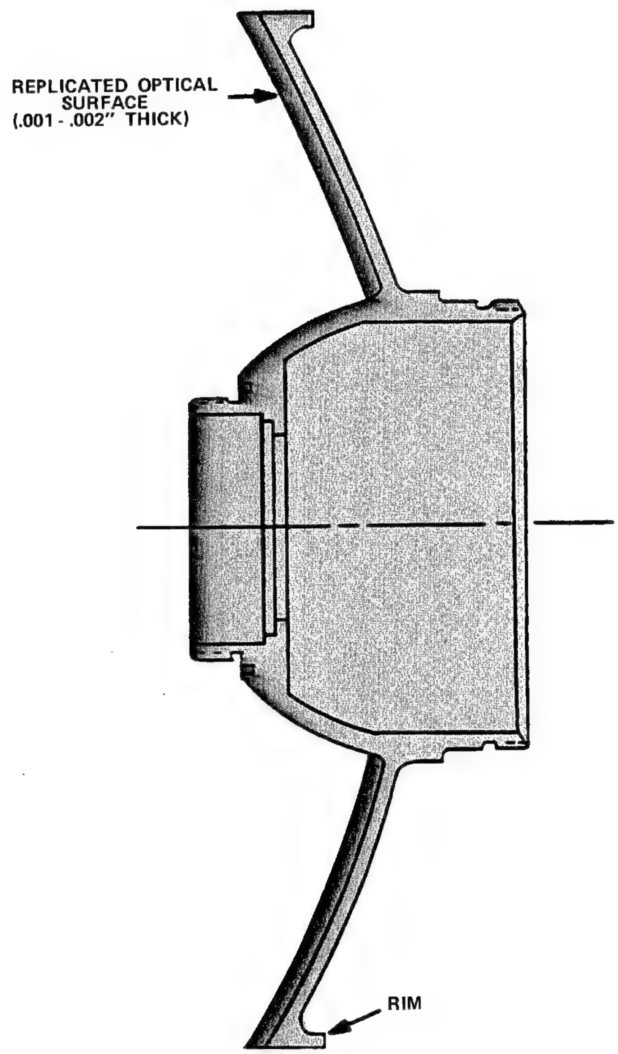


Figure 5

Epoxy Replication Evaluated

Effort was then directed toward developing an epoxy replicated mirror. The fabrication utilized an aluminum substrate, as shown in Figure 5. The replica was formed by precisely aligning a master optical mandrel with the substrate and permitting an epoxy bond to form between the surfaces. The cured replica, complete with an optical coating, was then separated from the mandrel to produce a finished mirror. Results from this effort were:

- Aspheric mirrors of excellent optical quality were replicated on gyro rotor substrates. The optical quality was consistent with the accuracy of the master surface utilized to form the replicas.
- Replication costs for high production rate are competitive.

- Environmental testing demonstrated the extreme durability of the epoxy utilized in forming the replica. It remained acceptable after several excursions between −55 C and 95 C and was unaffected by long term humidity.
- Accelerated life tests indicated that the reflective coatings on the face of the optical replica are substantially more sensitive to humidity than vapor deposited coatings on metal mirrors. It was not possible to achieve a coating that would survive 24 hours at 100 percent humidity and 120 F temperature. In all cases, the coatings showed deterioration within a few hours.
- Adequate optical axis alignment appears to be within the capability of the process despite fixturing problems encountered in the prototyping efforts.
- Replicated aspheric rotors are equivalent to the metal mirrors utilized in current series seekers in all optical and electrooptical characteristics evaluated.

Diamond Turning Acceptable

Diamond turning of optical surfaces was also investigated. A substantial portion of the cost of the diamond turned mirror is associated with the nickel and black chrome plating. To reduce the cost without sacrificing technical quality, the following approach was taken:

- Aluminum (6061-T6) substrates were fabricated and all non-optical surfaces were fine grit blasted. The blanks were then black anodized to produce surfaces comparable to black chrome but with less tendency to specular reflections.
- The mirror surfaces were machined by diamond turning to achieve an extremely smooth finish. Polishing was no longer required.
- The mirror reflective surfaces were coated with vapor deposited gold over an intermediate isolation barrier coating. Samples of the coatings survived 8 days at 100 percent humidity, 120 F with no appreciable loss of reflectance.

Tests of the diamond turned mirrors in an engineering seeker showed no deterioration in laser seeker optical performance. The diamond turned mirrors met all performance requirements.

This mirror development effort resulted in a reliable diamond turning process that meets system performance goals. Replicated optics were also developed to a satisfactory level. The lessons learned about fabrication of optics on thin shells are generally applicable to DOD systems where weight, environmental extremes, optical quality, and cost restraints must be resolved against system performance requirements.

Preamplifier Improved

The goal in the detector/preamplifier task was the design, development, and testing of a sensor assembly based on the use of a custom LSI integrated circuit preamplifier. The design included packaging concepts for the preamplifier and the detector, and assembly and packaging concepts for the entire assembly. A detector support/immersion lens was designed for use with the detector/preamplifier subassembly and a mold was designed and built to fabricate this part from injection molded polycarbonate. Figure 6 shows details of the LSI sensor assembly.

The design was originally based on utilization of the COPPERHEAD LSI preamplifier, which was in final development by Harris Semiconductor at the time the MM&T contracts started. As the Harris development effort was completed, it became apparent through characterization testing that the part, while adequate for COPPERHEAD, could not be used on the HLS if all performance requirements were to be met. As a result, a hybrid preamplifier using lid and chip components was developed and was eventually incorporated in all seekers.

However, LSI preamplifier development has continued under a separate MICOM MM&T contract with Martin Marietta's Microelectronics Center. From this effort, an improved LSI preamplifier is now available. Most of the MM&T sensor assembly design work will be directly applicable to the final production configuration, which is presently expected to use the new LSI preamplifier.

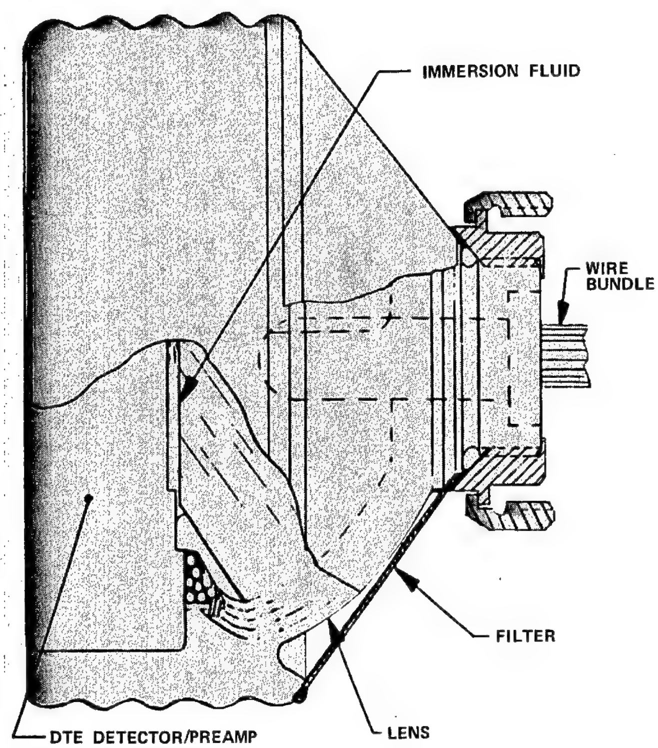


Figure 6

LSI Development Work

Two LSI circuit related tasks were undertaken in the MM&T program. These were the design and development of a new LSI to perform the tri-service code acquisition and acknowledgement functions at the seeker-missile interface (these functions are not present in COPPERHEAD) and the modification of an LSI integrated circuit developed for COPPERHEAD, which addresses the decoder memory circuitry in a code dependent format. The latter modification was necessary because the COPPERHEAD code identification logic is in true octal format and tri-service is not. Both tasks were undertaken because of the established advantages in manufacturing ease and cost of integrated circuits over their discrete or hybrid circuitry counterparts.

The complexity of the specified tri-service code load interface negated building the logic to perform this function in discrete component form. This was due to lack of sufficient circuit board space to accommodate even a small fraction of the required discrete circuitry. As a result, a hybrid circuit previously designed for another program was used as an interim device, while a custom LSI integrated circuit was developed for use in later seekers. The hybrid circuit contained 26 components, many of which were small and medium scale circuits that occupied 1.16 square inches of circuit board space. It was found to be extremely costly to fabricate and required highly skilled personnel for both assembly and test.

The "code acquisition" LSI integrated circuit was designed and developed between September 1978 and March 1979 by a joint team of HLS program and Microelectronics Center engineers. The die for this circuit measures 150 by 190 mils and contains 1092 transistors. It has input/output pads and is contained in an 18 pin ceramic DIP package. The part is made using standard 4000 series metal gate CMOS (Complimentary Metal-Oxide Semiconductor) technology and can be built by any of the many semiconductor suppliers who possess the 4000 series CMOS process.

In the 18 pin DIP package, the part occupies approximately 0.29 square inch of circuit board space. Its performance and reliability are better than those of the hybrid circuit it replaced. In addition, power dissipation and cost are greatly reduced. Because the part was designed to the standard tri-service laser code interface requirement, it has potential use on other DOD systems.

The memory address LSI integrated circuit used on the COPPERHEAD program was designed to accept code selection information in true octal format from rotary switches on the projectile bourrelet. The tri-service code load format deviates from true octal for some Band I codes and necessitated redesign of the LSI integrated circuit for use in HELLFIRE. Like the code acquisition LSI, the memory address LSI is a 4000 series, CMOS, seven mask design. It has a die size of 139 by 149 mils and contains 844 transistors. A small change to the die metalization (gate interconnection) was all that was required to accommodate the new logic format. The change was made in such a way that the same part may be used for either the COPPERHEAD or tri-service logic formats by trying one pin to logic 0 or logic 1.

Cost Slashed, Weight Cut

Injection Molded Acrylic Mirrors

By Bobby C. Park, U.S. Army Missile Command

Reduction in production costs by as much as a factor of 50 is just one attraction of injection molded acrylic mirrors for terminal homing seekers. In addition, the weight of these mirrors is only about 10 percent that of conventional glass or metal mirrors with ground surfaces. Furthermore, the potential production rate is higher than for any other processes or materials investigated during a MICOM MM&T program at Teledyne Brown Engineering (TBE).

TBE studied manufacturing methods and technologies for imaging mirrors designed for use in a spinning mass, gyro stabilized optics seeker (designed SMITHS—spinning mass integrated, terminal homing seeker). The investigation centered on a plastic, concave, aspheric mirror with a diameter of 3.72 in. and a system focal length of 1.852 in. Once the best manufacturing method was established, TBE outlined a detailed production plan, including estimates of costs, rates, and yields. As a result of the program, the procurement lead time and costs for conventional fabrication were significantly reduced.

Aspheric Mirror Required

The mirror was designed for the baseline seeker illustrated in Figure 1, where it is outlined by the dashed line.

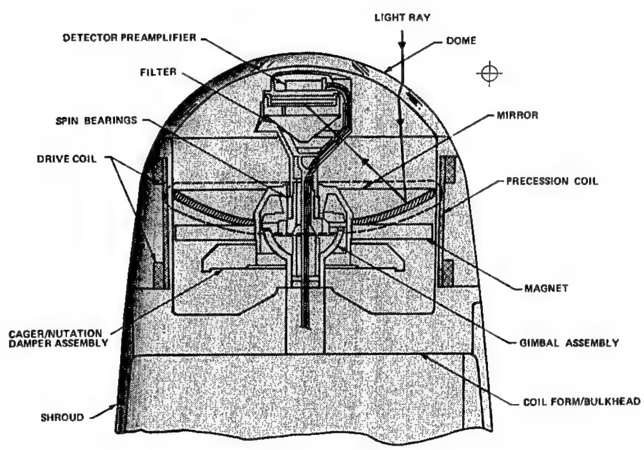


Figure 1

NOTE: This manufacturing technology project that was conducted by Teledyne Brown Engineering was funded by the U.S. Army Missile Command under the overall direction of the U. S. Army Office of Manufacturing Technology, DARCOM. The MICOM Point of Contact is Mr. Bobby Austin (205)876-8445.

The path of a light ray entering the dome is also shown. Because of design constraints, this system requires an aspheric (i.e., not completely spherical) primary mirror. Since fabrication of aspheric surfaces is not common in large volume production, the mirror would be very expensive if made from conventionally ground and polished glass. Thus, TBE undertook a program to identify more ecomonical, but equally reliable, production processes and techniques.

Their investigation covered conventional optical shop techniques for grinding and polishing glass or metal; epoxy replication of various substrates, including honeycomb; and injection or compression molding of plastics. Regardless of the fabrication process, the mirror requires a reflective coating. In this regard, TBE sought unsuccessfully to find an alternative to conventional vacuum evaporation of metallic films.

Injection Molding Chosen

Table 1 compares the three fabrication methods investigated, showing advantages and disadvantages of each. The data in this table are based on a total procurement of 25,000 coated mirrors for installation in seekers produced at a rate of 500 per month. As a result of the tradeoff study summarized in the table, TBE picked injection molding of plastic as the best fabrication process. This choice was based on four significant factors:

- Reduction in production costs to as little as 2 percent of those for conventional grinding and polishing and 10 percent of those for replication.
- Significant weight reduction compared to conventional optical materials and most replicas. With the lower weight, spin and gimbal bearing reliability in the seeker will improve.
- Potential for by far the highest production rate.
- Adequate optical quality and imaging performance.

Injection (rather than compression) molding was chosen because the cycle time was believed to be shorter. However, the actual cycle time for injection molding has proven longer than expected and compression molding may be a competitive process. Replication was rejected because it does not offer the low cost and high production rates of molding, although technical risk in producing an acceptable mirror is probably reduced.

Several potential plastic materials were investigated for use with the injection molding process. Table 2 gives relevant physical properties and molding characteristics of the plastics that were considered. Based on this information, polycarbonate (Lexan), polyphenylene oxide (Noryl), and high temperature acrylic (Plexiglas-H) could be used for the mirror. The high temperature acrylic was chosen for process development based on molder recommendations that it is easier to mold, gives a more accurate surface figure, and is more stress free after molding. The Plexiglas H is also cheaper (Lexan and Noryl cost 35 and 60 percent more, respectively) but since material represents only 3 percent of total mirror costs, the savings is not significant. The other two polymers, however, also appear adequate for production applications.

Gold Coating Preferred

Both gold, with a protective overcoat for durability, and aluminum, with a silicon monoxide overcoat, were considered suitably reflective coatings. Gold was selected on the basis of higher reflectance in the near infrared region. It gives 90 to 98 percent reflectance at 1 micrometer wavelength vs. 85 to 94 percent for aluminum. Because of the small amount required, the gold was not expected to significantly effect cost in production.

Processes for both electroless deposition and electroplating were identified but vendors reported that these processes are not suitable for acrylic or polycarbonate plastics. Therefore, conventional thermal evaporation was chosen as the coating process. Although the coating costs are about 50 percent higher than those for coating glass mirrors because of increased vacuum pumping time, this difference does not drastically increase overall cost of the mirror.

Uses Metal Mold

The steps involved in injection molding of a mirror are shown in Figure 2. The mold, which is a negative of the desired optical surface, is made from metal to withstand the temperatures and pressures involved and to provide long life. The tooling is expensive because the negative of the optical surface must be ground and polished and because its production requires both an experienced

Evaluation Points	Manufacturing Methods		
	Conventional Optical Grinding and Polishing	Replication	Injection or Compression Molded Plastic
Initial tooling costs	—	$7,500 for 5 masters and 50 submasters	$8,800 for single cavity mold
Lead time before production begins	2 months	4 months	3 months
Per part cost in production	$250 to $1,000	$25 to $50	$5 to $15
Achievable production rate	Depends on cost: Higher cost buys production capacity, or use multiple sources	600 mirrors/month with tooling specified above, but additional capacity can be bought	4,400 mirrors/month in three shifts equals single shift coating capacity
Competitive facilities available in U.S.	Yes; numerous optical shops	Yes; three vendors identified	Yes; five vendors identified
Materials or equipment supply problem	None foreseeable	None foreseeable	None foreseeable
Skill required for production	Opticians skilled in aspherics required throughout production	Optician skilled in aspherics required to make initial tooling, about 4 months; optician or engineer required to check production output periodicially	Optician skilled in aspherics, mold designer, mold maker required to make initial tooling, about 3 months; optician or engineer required to check production output periodically
Quality level achievable	Ultimately very good, depends on cost; adequate for LTHS application	Within 0.3 μm of conventionally ground and polished master; adequate for LTHS application	Equal to conventional commercial optical practice; thought to be adequate for LTHS application
Environmental stability	Adequate	Adequate on proper substrate (probably aluminum die-casting)	Adequate for baseline design with proper choice of polymer
Mirror weight	Density: 0.081 lb/cu in. (pyrex) Volume: 5.5 cu in. Weight: 0.443 lb (Thicker substrate required to withstand deforming under grinding and polishing pressures)	Density: 0.098 lb/cu in. (aluminum) Volume: 1.0 cu in. Weight: 0.098 lb	Density: 0.042 lb/cu in. (acrylic) Volume: 1.0 cu in. Weight: 0.042 lb

Table 1

optician and mold designer. But obviously, these costs, prorated over a large production run, are far less than those for grinding and polishing each mirror.

In injection molding, plastic pellets are metered from a hopper to a heating chamber, which is at a temperature near the melting point of the pellets. The plastic softens and is injected into the mold by a screw or ram plunger under pressures up to 30,000 psi. (Optimum operating temperature and pressure are preset and controlled automatically by the machine.) When the plastic freezes and hardens in the mold (which is cooler), pressure is released and the mold halves open to eject the molded mirror blank, which is removed by an operator. (No release agent is used on the mold to avoid contamination.)

Parameter	12	AC	HAC	PC	PPO	PSF
Molding qualities	Excellent	Excellent	Good	Fair	Good	Fair
Specific Gravity	1.04 to 1.09	1.19	1.16	1.20	1.06	1.24
Water absorption, %, in 24 hr immersion, 0.125 in. thick	0.03 to 0.1	0.3	0.2	0.15	0.07	0.22
Deflection temperature, at 264 psi, F	200 to 210	198	221	265 to 285	265	345
Maximum recommended continuous service temperature, F	140 to 180	175 to 200	200 to 230	250	260	300 to 345
Thermal expansion coefficient, in./in./F, 70 F	3 to 8 x 10^{-5}	3.8 x 10^{-5}	3.1 x 10^{-5}	2.8 x 10^{-5}	1.4 to 3.7 x 10^{-5}	3.1 x 10^{-5}
Flexural modulus, psi	3.3 to 4.7 x 10^5	4.6 x 10^5	5.0 x 10^5	3.4 x 10^5	3.6 to 10.4 x 10^5	3.7 to 3.9 x 10^5
Cost per pound, dollars, ~300-pound lots (1975)	0.30 to 0.40 (est.)	0.56	1.00	1.35	1.60	2.00 (est.)

PS – Polystyrene
AC – Acrylic [Rohm and Haas Plexiglas V(811)]
HAC – High temperature acrylic (Rohm and Haas Plexiglas-H)
PC – Polycarbonate
PPO – Polyphenylene oxide
PSF – Polysulfone

The properties of plastic molding resins depend on the particular formulations chosen. For most resins, formulations are available for general use and for resistance to

- High impacts
- High temperatures
- Ultraviolet exposure.

Table 2

The operator also monitors the gauges and indicators and periodically refills the hopper.

The machine runs automatically, requiring a 3 minute cycle for mirror fabrication. With optical parts a continuous, three shift operation is most efficient. Because dimensions are so critical, stabilization of the machine each morning would take several hours if it were shut down in the evening.

Post Molding Operations

After molding, the gate and sprue are removed from the mirror and a center hole is added in a single operation. A special tool called a trephine, which resembles a hole saw, is used. The trephine, held in a milling machine chuck, descends slowly to a preset depth in the mirror. The speed is carefully controlled to avoid overheating or fracturing the plastic. Figure 3 shows a section of a molded mirror indicating by dotted lines the configuration before and after this operation.

Either the molding or trephine operator visually inspects all mirrors for bubbles, foreign matter, surface quality, or obvious warpage. Typically, one mirror in ten will be checked for optical performance. Following inspection, the mirrors are cleaned by flushing with a

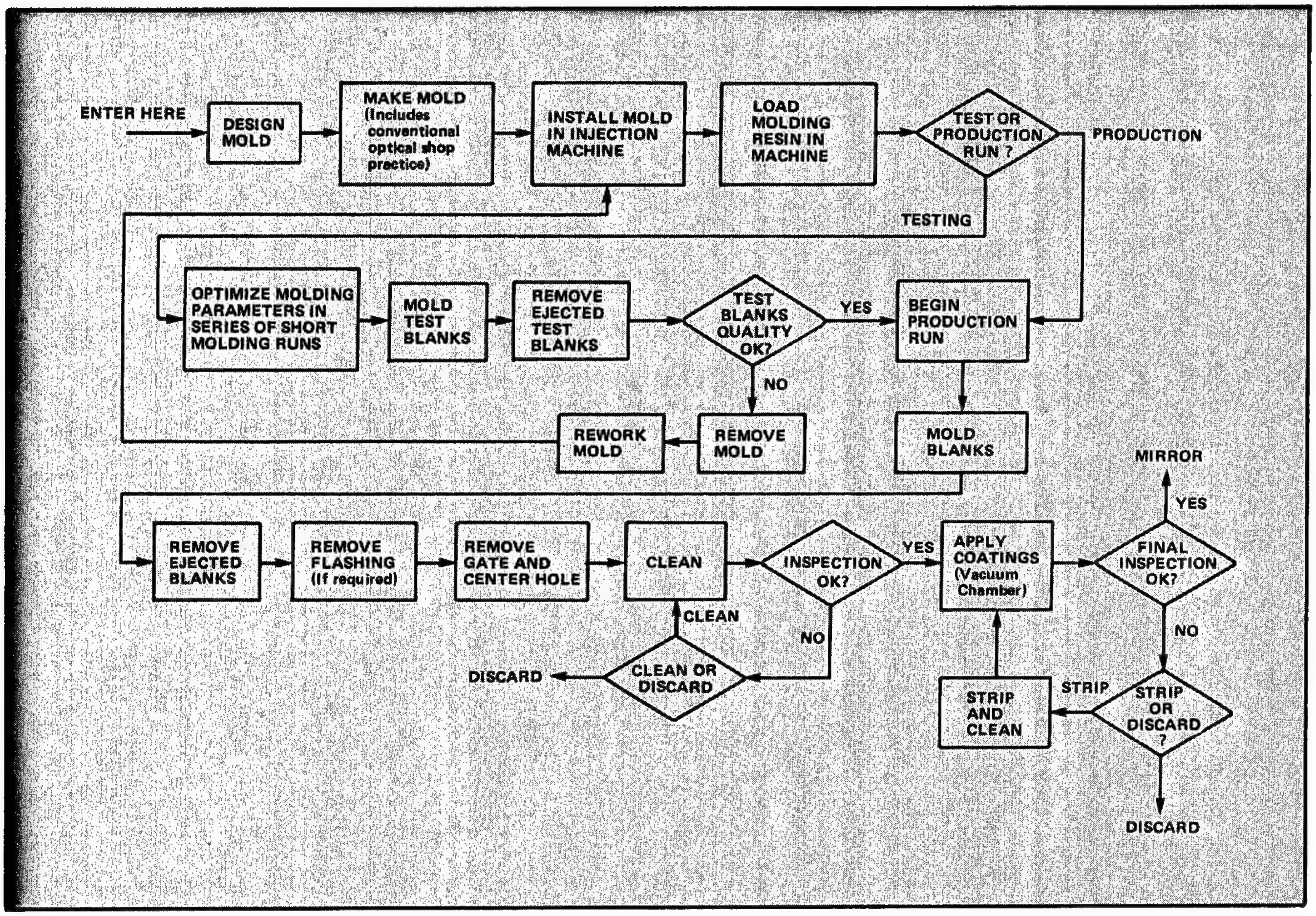


Figure 2

solvent, such as Freon, that will not attack the plastic. This washing removes residual monomers, dust particles, residue from degating, and oils or vapors that have evaporated on the mirror. The mirrors are handled with lint free gloves in all subsequent operations.

Vacuum Coating

For coating, the mirrors are installed in permanent fixtures or racks in a vacuum chamber. This may be done in a heavily ionized local atmosphere. (Where mirrors are shipped to a separate coating vendor, they will have to be unpacked, inspected, and cleaned as necessary prior to coating.) The racks hold the mirrors in a way that ensures uniform coating. With the racks loaded, small tungsten evaporation boats in the chamber are loaded with the coating material, the vacuum chamber is closed and sealed, and rough pumping begins. From this point, coating operations are automatic, freeing the operator to perform other tasks, such as unpacking, inspecting, and cleaning the next batch of mirrors.

During pump down (with the chamber pressure at .01 to .001 torr), a glow discharge sets up to further clean the parts. Low-energy ions are produced that effectively scavenge thin layers of surface contaminants and adsorbed gases. Evaporation begins when the pressure reaches .00002 torr. High currents passing through the evaporation boats heat them to incandescence. As a result, vapors of the coating material move out from the boats in a Lambertian pattern and condense on the cool surfaces in the chamber, including the mirrors.

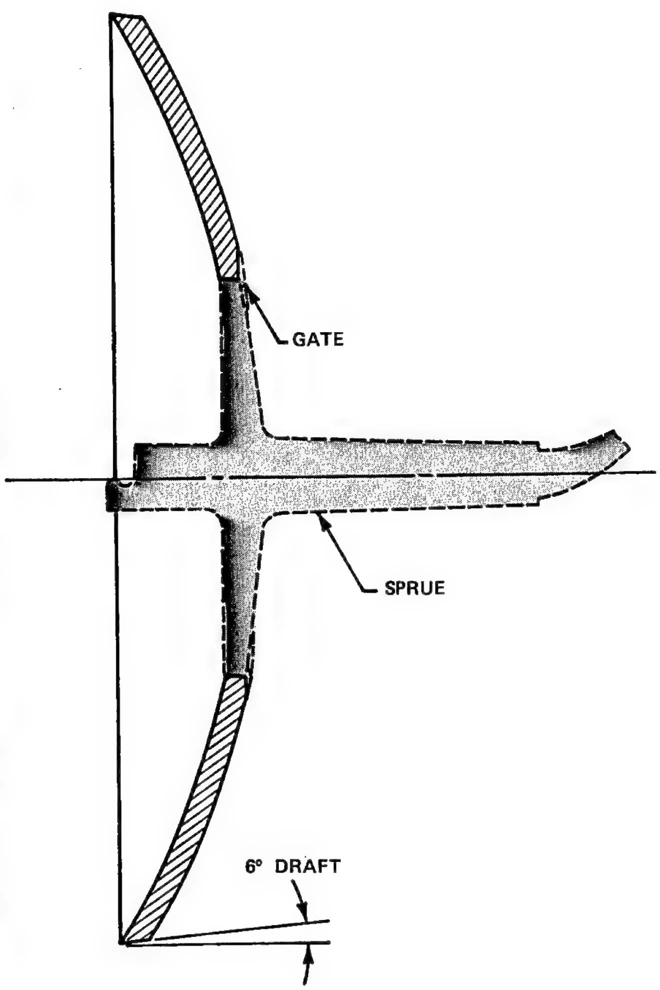


Figure 3

Coating thickness is controlled by either:

- deposited thickness monitors that measure the mass of evaporated material that has condensed on a quartz crystal changing its resonant frequency
- Optical thickness monitors that measure the actual transmission or reflection of samples in the chamber as coatings are applied.

Either type of monitor is accurate to ± 10 nanometers.

Cycle time for coating plastics is two or three times that required for coating glass, depending on the amount of water absorbed in the plastic. An 18 inch diameter chamber holding glass optics will cycle through a coating operation in about 30 minutes. With plastics, the cycle might be as long as 90 minutes.

When the proper thickness is obtained, the vacuum chamber is shut off with valves from the vacuum pumps, which continue to run. Dry nitrogen or air is bled into the chamber to bring it back to atmospheric pressure and it is opened. The mirrors are removed from the racks and visually inspected for pinholes, opacity, coating roughness, and coating cracks or blisters. At least one mirror per lot is set aside for additional testing and the lot number is marked on the back of all mirrors.

Production Plan Developed

TBE devised a production plan for injection molding of mirrors that calls for two molding operators, as shown in the Table 3 breakdown of tasks and times. The need to remove an ejected mirror every 3 minutes ties one operator to the molding machine. That operator visually inspects the molded parts, monitors the machine, and keeps the material hopper full. Working on batches of mirrors, the second operator removes the gate and sprue, cleans the mirrors, and packs them for shipping, if necessary. This operator also checks optical performance on a sampling of mirrors and visually inspects all mirrors after cleaning. All tasks performed by both operators can be done within the machine cycle of 3 minutes.

Tasks and times for coating operations, which require a single operator, are shown in Table 4. Here again, the operator can perform his tasks during the vacuum chamber cycle.

Possible facility layouts for the mirror fabrication are shown in Figures 4 and 5. Coating, cleaning, and molding operations are separated to prevent contamination of mirror surfaces by particles and aerosols from the molding machine after cleaning. The milling machine, which produces acrylic dusts and fines, is likewise isolated. Because of its high noise level, the vacuum roughing pump is located outside the coating room.

Performance Test Needed

Although most defects are caught by visual examination after both molding and coating, slight surface changes

Task No.	Activity	Time
	Machine Activities	
1	Start. Mold Closes. Material Injected.	50 sec
2	Pressure Released. Mold Stays Closed. Blank Cures.	125 sec
3	Mold Opens. Blank is Ejected. Operator Removes Blank.	5 sec
	Machine Total	180 sec/blank
	Operator 1 Activities	
1	Remove Ejected Blank from Mold. Inspect Blank. Place in Tray.	30 sec
2	Check Molding Machine Operating Parameters.	30 sec
3	Check Fullness of Hopper by Noting Number of Parts Molded.	10 sec
4	Load Hooper if Necessary in Several Succeeding Molding Cycles.	120 sec/cycle
	Operator 1 Total	60-180 sec/blank
	Operator 2 Activities for 20 Blanks	
1	Remove Gate and Center Hole from Blanks.	20 min
2	Load Blanks in Racks for Cleaning Bath.	2 min
3	Clean Blanks.	5 min
4	Remove Blanks from Cleaning Rack. Visually Inspect.	10 min
5	Perform Functional and Dimensional Checks on Two Mirror Blanks.	10 min
6	Load Blanks in Tray in Shipping Container.	3 min
7	Seal Shipping Container if Necessary, Relieve Operator 1, or Reclean Dirty Mirrors	0-10 min
	Operator 2 Total	50-60 min/ 20 blanks

Table 3

that can affect imaging performance can go undetected. This is why a sampling of mirrors is performance tested, as mentioned earlier. Because the molding process is so repeatable, a one-in-ten check is adequate. Figure 6 shows the functional test setup for performance inspection.

The condenser lens (top) focuses a light source, S, onto an off axis parabolic mirror (left) through the single color filter, F, which passes a visible wavelength. The mirror (above) diverts the optical path. A resolution target, T, perhaps a three bar pattern, placed at the focal point, is imaged at infinity. The test mirror, TM, is held

Task No.	Activity	Time
	Vacuum Chamber Activities for 40 Mirrors	
1	Start. Close Chamber. Operate Valves. Start Roughing.	1 min
2	Begin Glow Discharge.	20 min
3	End Glow Discharge	5 min
4	Operate Valves. Begin Diffusion Pumping.	5 min
5	Start Evaporation.	40 min
6	End Evaporation.	3 min
7	Operate Valves. Vent Chamber.	1 min
8	Chamber Open.	5 min
9	Chamber Reloaded.	10 min
	Chamber Total	90 min
	Operator Activities for 40 Mirrors	
1	Close Chamber. Activate Controls.	1 min
2	Unload Coated Mirrors from Rack. Mark Lot Number.	8 min
3	Inspect Mirrors Visually.	10 min
4	Pack Coated Mirrors in Shipping Container.	5 min
5	Test Reflectance. Test Adhesion, Durability on Sample Mirror.	6 min
6	Unpack New Blanks. Clean.	40 min
7	Load New Blanks on Rack.	6 min
8	Blow Dust Off Racks.	3 min
9	Swap Racks in Chamber.	6 min
10	Add Material to Evaporation Sources.	4 min
11	Close Chamber.	1 min
	Operator Total	90 min

Table 4

in an accurately positioned fixture together with a flat folding mirror and a microscope, MS. The parabolic mirror to their left is designed to simulate the effect of the seeker dome. The test operator views the image of T at the focal point of TM through the microscope and assesses the imaging properties by noting the bar group just resolved or by some other criterion. Performance is compared with accepted limits.

High Production Rate

Using the production processes described here, TBE projects a production rate of 4,400 mirrors per month. Limited by the coating rate, this figure is based on a three shift molding operation and one shift operation of a 40 blank capacity vacuum coating chamber. This rate could, of course, be doubled by going to a two-shift coating operation or to a second source for coating.

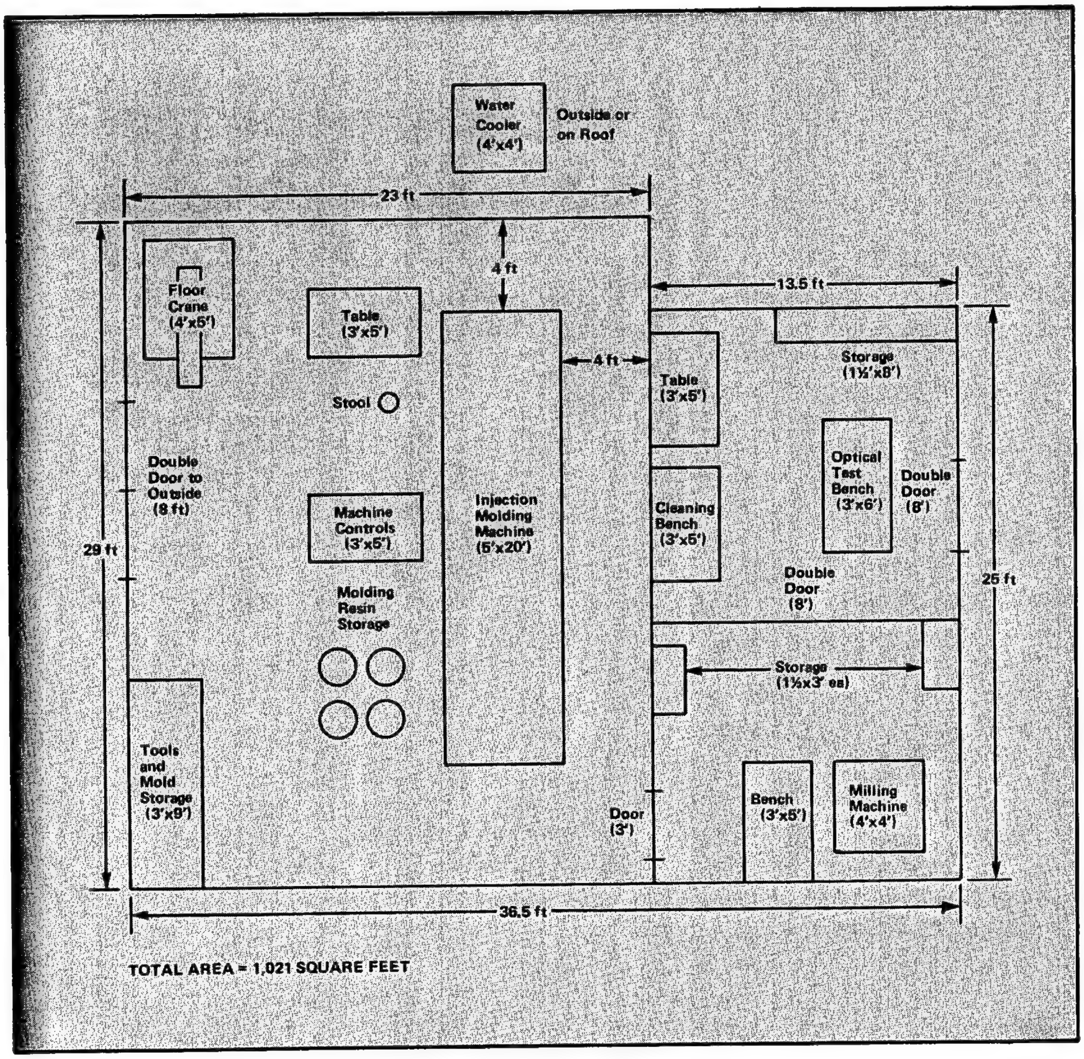


Figure 4

TBE recommends outside purchase of mirror units from specialty vendors rather than in-house fabrication by a prime contractor because:

- The production equipment is costly, complex, and specialized and must be fully utilized to be profitable.
- The mold designer, mold maker, molder, and coating engineer all have specialized, proprietary knowledge regarding their crafts that will be concentrated in specialty shops.
- The competitive situation in the plastic optics and coating industries insures lowest prices for products and services.

In the case of the mirrors studies, TBE recommends purchase in lot sizes exceeding 1500 units. This is because the potential production rate greatly exceeds seeker production of 500 per month and because large lot purchase results in significant cost savings.

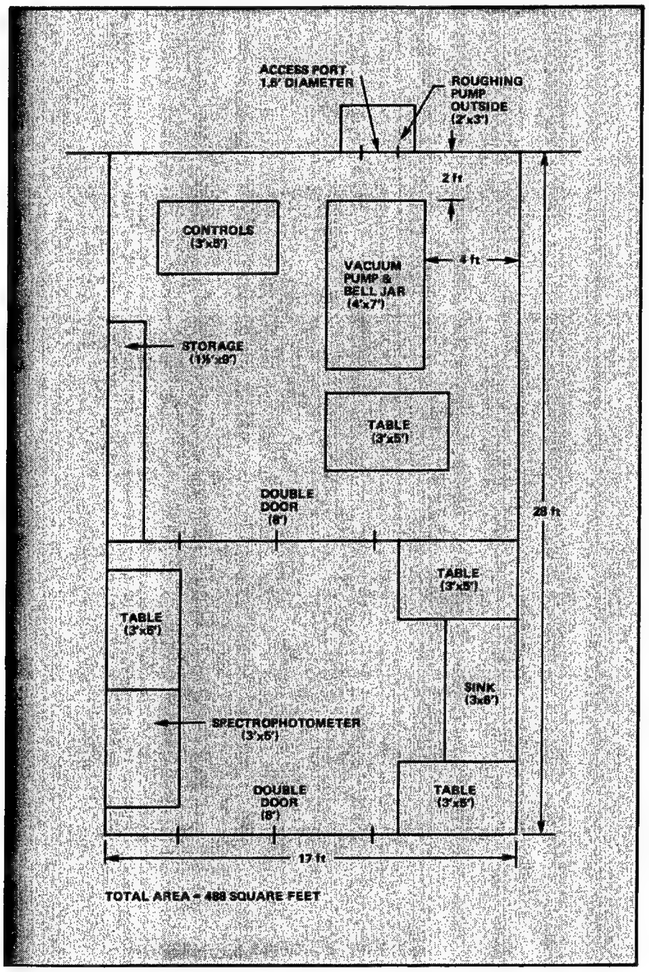


Figure 5

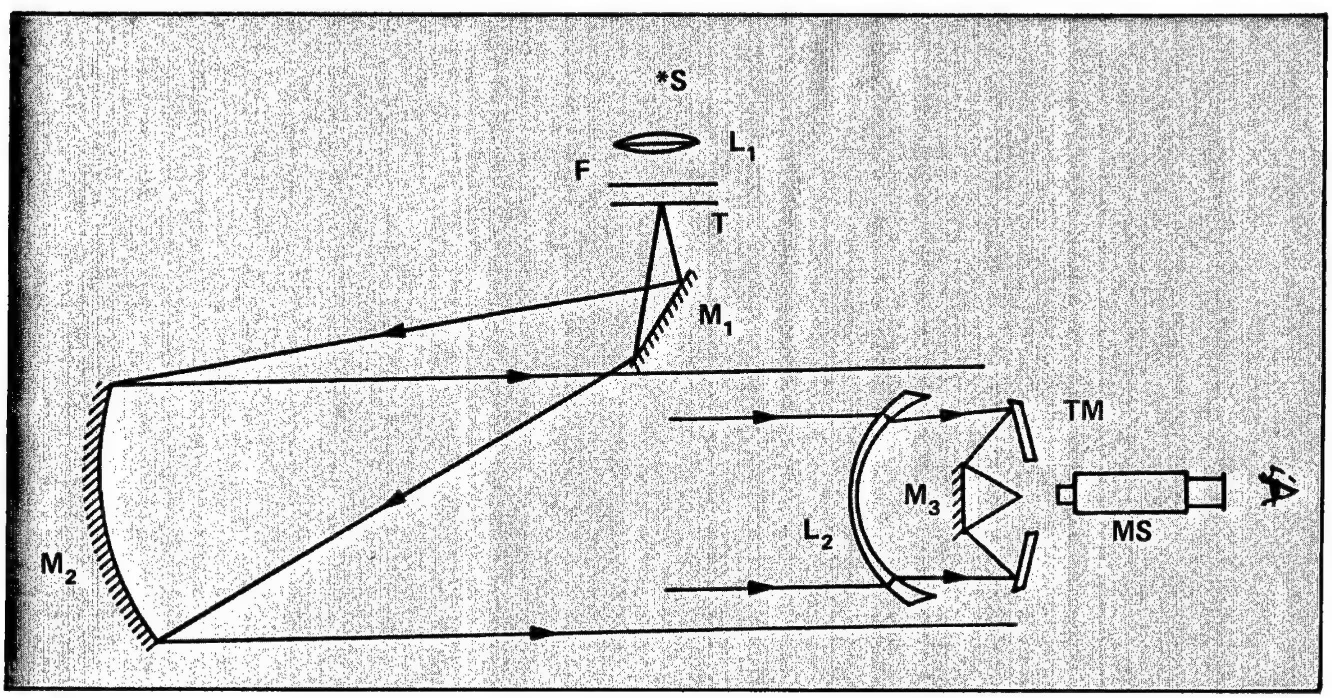


Figure 6

Injection Molded Parts Cut Costs

Reinforced Plastics for Missile Seekers

By Bobby C. Park, U.S. Army Missile Command

Replacement of metal with glass reinforced thermoplastics in the primary structure of terminal homing seekers results in significant cost savings—a plastic shroud and support structure for a seeker electronics section developed at Teledyne Brown Engineering TBE costs less than one half as much as similar aluminum structures. TBE's development work was conducted on a spinning mass, gyro stabilized optics seeker during a MICOM MM&T effort. Development of injection molded mirrors for this seeker is reported in an accompanying article. A third article in this issue reports on the integration of these efforts into development of a low cost seeker for future missiles.

Important Conclusions Drawn

During the program reported here, TBE investigated nonmetallic materials for the shroud, assessed molding processes, designed the nonmetallic shroud, and developed a manufacturing plan for high volume production. Major conclusions from this effort, in addition to that on cost savings, were:

- Injection molding is the best process for fabricating nonmetallic seeker components. It has the greatest versatility with regard to the shape and intricacy of parts that can be molded and the variety of materials that can be accommodated. The fast injection molding cycle time results in low molding costs and high production rates.
- Injection molded glass reinforced engineering thermoplastics—such as 40 percent glass reinforced polysulfone and 30 percent glass reinforced polyphenylene oxide (noryl)—can fulfill the structural and environmental requirements for spinning mass laser terminal homing seekers.
- Injection molded 40 percent glass reinforced polycarbonate foam is also an excellent candidate material for the electronics shroud and support structure. Its strength to weight ratio is higher than that of non-heat treated aluminum and the foaming action, which permits easy filling of thick sections, simplifies mold design.
- To obtain consistently high quality parts from engineering thermoplastics containing high percentages of glass reinforcement, reciprocating screw, injection molding machines rather than plunger machines are preferred. Plunger machines do not have the plasticizing capability to produce the homogeneous melt required for successful injection molding of these materials.
- Successful injection molding of the glass reinforced engineering thermoplastics requires careful mold design and fabrication, experienced molders, and comprehensive quality control of the entire molding process. Molds must be extra strong, heat treated, and highly polished with heating features that provide mold temperatures from 60 to 300 F. Proper design and location of gates and runners plus proper nozzle design are also extremely important.

NOTE: This manufacturing technology project that was conducted by Teledyne Brown Engineering was funded by the U.S. Army Missile Command under the overall direction of the U. S. Army Office of Manufacturing Technology, DARCOM. The MICOM Point of Contact is Mr. Bobby Austin (205)876-8445.

Several Materials Meet Need

From a technology review of approximately 30 materials, TBE selected eight glass-reinforced engineering thermoplastics as potential laser seeker structural materials. The advantages of reinforced plastics over their unreinforced counterparts show that the addition of 30 percent glass reinforcement can double tensile strength and triple flexural modulus, while reducing shrinkage by 50 to 85 percent.

The glass reinforced foamed thermoplastics selected (nylon and polycarbonate foam) are excellent candidates because their strength to weight ratios are two to five times greater than those of metals. Furthermore, their creep rate, tensile properties, and load carrying ability are significantly superior to those for basic unfoamed, unreinforced resin (see Table 1).

Injection molding was selected for fabrication after investigation of ten processes. Table 2 compares these processes. In addition to its greater variabil:ty and fast cycle times, injection molding is the best method for fabricating tapered hollow cylindrical parts, such as the seeker electronics shroud, that are open at each end and require precision molding of both inner and outer surfaces.

Design For Moldability

The seeker design concept for the MM&T effort had a hemispherical ogive external shape, as seen in Figure 1 of the article on mirror technology. To fit this concept TBE developed two electronics shroud configurations. The basic shroud (Figure 1) is thin walled (0.125 in.) and was designed for conventional injection moldable glass reinforced thermoplastics. Information gathered in the design review indicated that this design would provide an easily molded part without sinks and voids. Three pairs of longitudinal ribs spaced 120 degrees apart, with full length longitudinal slots on the inside of each rib, provide support for three aluminum mounting strips for printed circuit boards (PEBs). These mounting strips accommodate PCBs that are 6 inches long and 3.87 inches wide. The mounting configuration for the PCBs is illustrated in Figure 2.

Aluminum mounting strips are used because thermal analysis indicated they were required to provide conductive heat paths that would keep PCB temperatures below 260 F. If board temperatures can be allowed to increase to 300 F without affecting reliability, performance, cost, or service life of the electronics, the aluminum strips can be replaced by molded in supports. An all

Property	Nylon Type ξ		Polycarbonate		Polystyrene		Polypropylene		ABS	
	Base Resin	Foam	Base Resin	Foam	Base Resin	Foam	Base Resin	Foam	Base Resin	Foam
Specific Gravity	1.13	0.93	1.20	0.94	1.07	0.84	0.90	0.73	1.04	0.84
Tensile Strength (psi)	9,000	12,000	9,500	14,000	5,000	5,000	4,000	3,000	7,000	7,000
Flexural Strength (psi)	7,400	20,000	13,500	14,200	8,000	8,500	6,000	6,000	11,000	12,000
Flexural Modulus (psi x .00001)	2.45	8.5	3.5	5.8	4.5	7.5	2.0	4.0	4.6	7.5
Deflection Temperature Under Load at 264 psi (F)	130	385	270	276	190	190	135	162	220	210

Table 1

Molding/Forming Process	Can Mold or Form to Close Tolerance (< ±0.005 in.)	Can Mold or Form 3-Dimensional Parts	Requires Finish Operations to Provide Holes, Undercuts, Fasteners, etc.	Can Accommodate Both Thermosets and Thermoplastics	Can Accommodate Glass-reinforced Materials	Can Accommodate Structural Foams
Blow Molding	No	Yes	No	No	No	No
Calendering	Yes	No	Yes	No	No	No
Casting	Yes	Yes	Often	Yes	Yes	Sometimes
Centrifugal Molding	On Outer Surface Only	No	Yes	No	Yes	No
Compression/Transfer Molding	Compression-No Transfer-Yes	Yes	Yes	No	Yes	No
Filament Winding	On Inner Surface Only	Yes	Yes	No	Yes	No
Extrusion & Pultrusion	No	No	Yes	No	Yes	No
Injection Molding	Yes	Yes	Sometimes	Yes	Yes	Yes
Rotational Molding	On Outer Surface Only	Yes	No	Yes	No	No
Thermoforming	No	Yes	Yes	No	Yes	No

Table 2

plastic shroud would result in a further cost reduction of about 40 percent.

Both ends of the shroud contain screw holes for attachment to the coil and the bulkhead. Although they were machined after molding during the MM&T effort, in high volume production these holes would be molded in place.

The second design was a thick walled (0.250 in.) foamed shroud (Figure 3) that takes advantage of the ability of foamed plastics to easily fill thick sections without significant shrinkage during curing. This design provides a high stiffness to weight ratio.

Instead of longitudinal ribs, the foamed shroud incorporates flat bosses of the same length as the ribs. A high temperature silicone adhesive is used to bond the aluminum strips to these bosses.

In the seeker assembly, the forward end of the electronics shroud attaches to a coilform, which was also designed for injection as part of the MM&T effort. This part is in the general shape of a cup with the bottom containing a central hub supported by a ribbed bulkhead. When assembled, the hub accommodates the gimbal post, which, in turn, supports the gimballed and rotating parts of the seeker. The dome attaches to a thick ring section at the forward end.

Properties Dictate Mold Design

Molds were designed and fabricated for both the basic and the foamed shroud and the coilform. Because of their high flow viscosities, glass-reinforced thermoplastics are generally difficult to mold. Thus, although the mold configurations were relatively simple, the material properties called for special mold features:

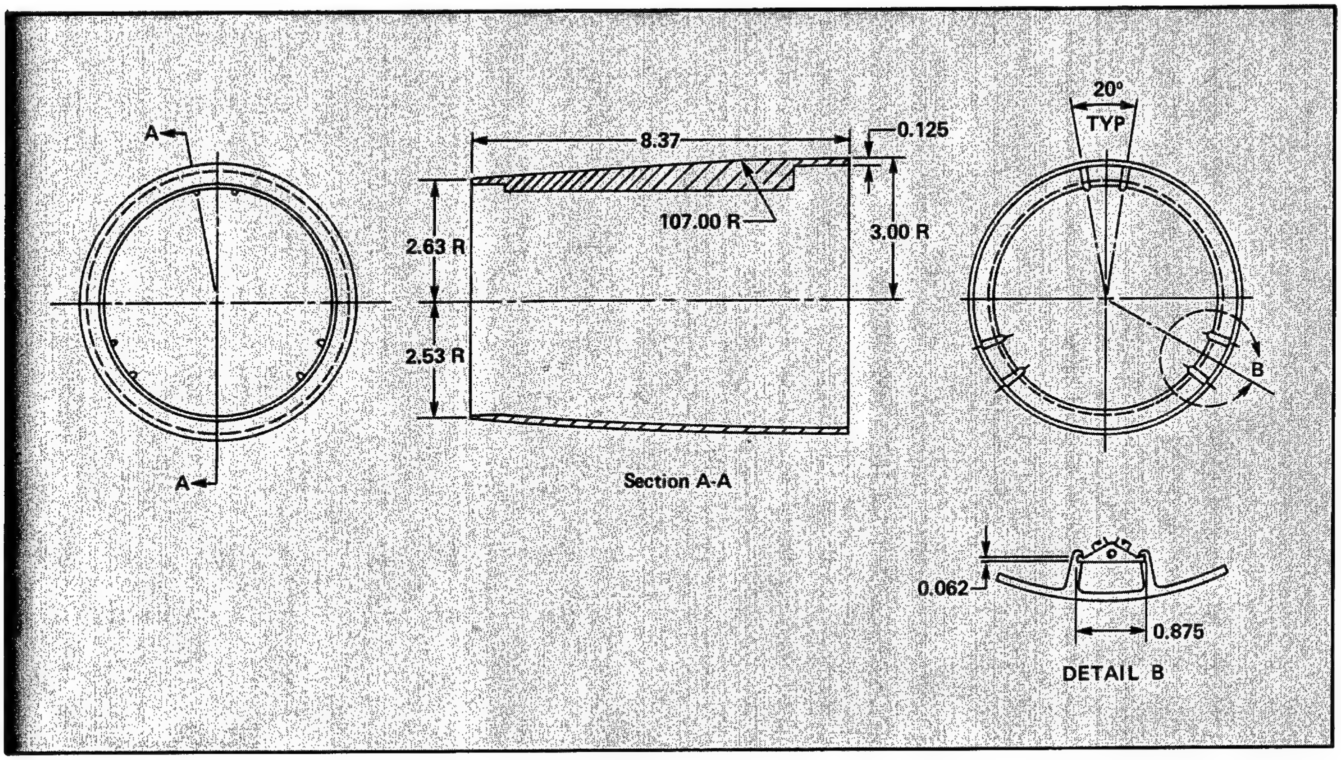


Figure 1

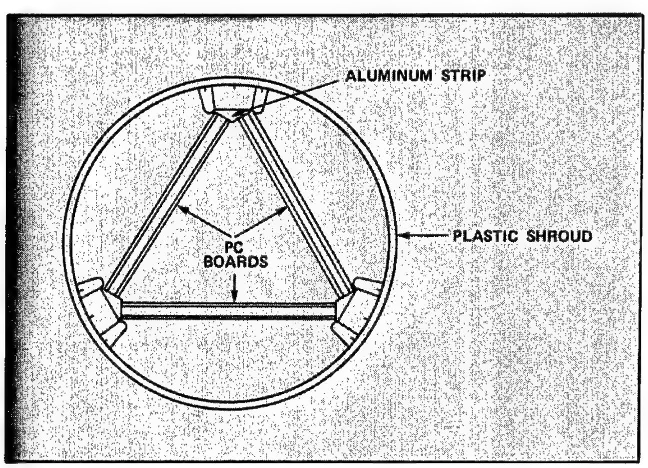


Figure 2

- Smooth, full-round runners, as short as possible and with a minimum ⅜ inch diameter
- No sharp corners in gates, sprues, and runner systems
- Gate land dimensions no larger than 0.030 inch unless otherwise specified
- Cold slug wells where practical
- Large short sprues with a minimum diameter of 5/16 inch at the orifice end
- All shroud cores equipped with water bubbler unit for more effective heating and cooling
- Water passages no smaller than ⅜ inch diameter on both front and back mold cavities
- Use of prehardened mold steel.

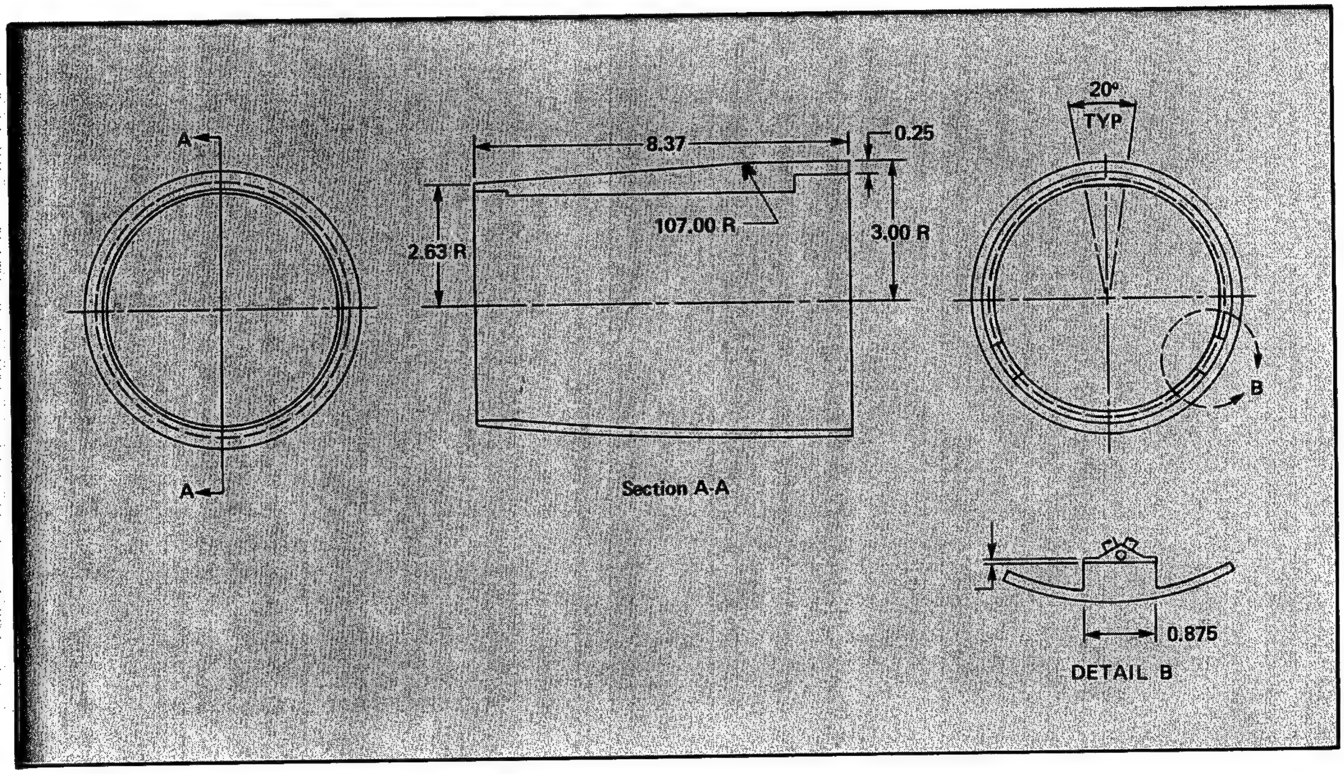


Figure 3

The molds for the basic and foamed shrouds include a single female cavity that attaches to the fixed platen of the molding machine, two male cores that attach to the moving platen, and a stripper plate that pushes the molded shroud off the core when the moving platen is extended. The single female cavity suffices, since the outer contour of both shrouds is the same. The male cores that form the longitudinal support ribs of the basic shroud and the bosses of the female shroud are changed to convert from one shroud to the other.

Simple Molding Operation

Figure 4 illustrates the operation of the shroud molds. The upper left photograph shows the foamed shroud mold fully opened before initiation of the molding cycle. The three spoked runners that feed the plastic to the mold from the sprue, or central inlet, are clearly visible. Two chains attached to the stripper plate and the stationary platen to activate the stripper plate are also seen.

The rear edge of the shrouds is formed by the male core and the stripper plate. On the basic shroud, the stripper plate forms approximately one third of the edge thickness. This is the area contacted by the stripper plate as it pushes the shroud off the core.

The upper right photograph shows the mold closed, ready for injection of the plastic material. In the lower left photograph, the molds have been opened just far enough to show the molded shroud on the core before ejection by the stripper ring. In the last photograph, the moving platen has been fully extended so that the stripper plate has ejected the shroud from the core.

The coilform mold has a male core that attaches to the moving platen of the molding machine, a base plate that

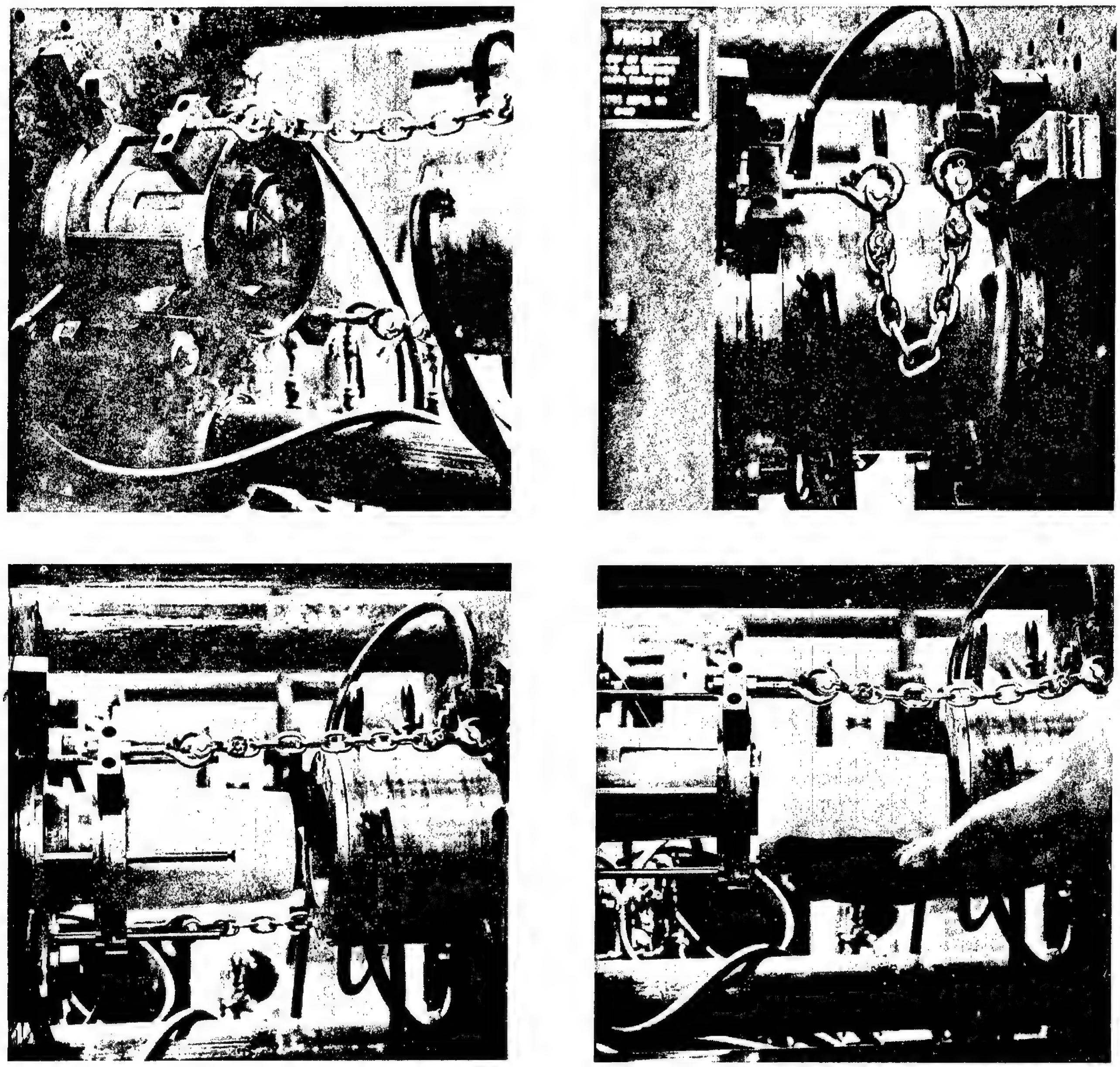


Figure 4

attaches to the stationary platen, and two removable cavity halves. The male core forms the inside of the coilform, including the hub, support ribs, and inside surface of the bulkhead. The base plate forms the outer surface of the bulkhead, and the two removable cavity halves form the outside of the cylindrical portion, including the thickened ring section at the forward end and the bosses and tabs at the rear.

Subcontractor Molds Shrouds

In the MM&T effort, all shrouds were processed by a subcontractor on a plunger type machine with a 300 ton clamping capability. The maximum injection capacity of this machine is 16 ounces based on general purpose polystyrene. This translates into a capacity of 24 ounces for typical glass reinforced materials that have specific gravity of about 1.5. Completely hydraulic, the machine can exert a 30,000 psi injection pressure.

Several machine assessories were particularly important in molding the shrouds. The machine has a precision feeder based on material weight and a dehumidifier hopper dryer. The heating chamber is controlled by three temperature controllers and nozzle heat is controlled separately by a rheostat. A preposition injection plunger control permits the plunger to be positioned at any preset stop after injection. Another important feature is the sprue break control, which permits the complete injection sled assembly to be retracted from the mold after injection. This was used to create an extremely effective positive shutoff nozzle.

Particular care was devoted to the initial selection and subsequent modification of injection nozzles. The nozzles successfully used to mold sample parts in different materials are described in Table 3. (Polysulfone is not shown since it could not be successfully molded on the available machines. Satisfactory polysulfone parts were eventually molded on a reciprocating screw machine.) All nozzles were equipped with one to three moderate wattage heater bands, the number depending on the length of the nozzle.

The successful molding of foamed structural plastics requires a positive shutoff nozzle, which prevents nozzle leakage between cycles. Standard, spring loaded, ball type and needle type shutoff nozzles were tried, but neither could effectively control leaking. However, a third type of nozzle that utilizes the sprue break capability of the molding machine to mechanically open and close the passages inside the nozzle proved quite effective.

Material	Description of Nozzle
Nylon	Reverse taper nozzle with 3/4 inch diameter bore tapered to match machine; 1/4 inch diameter orifice
Polycarbonate	General-purpose or standard design nozzle with a shortened land dimension of 3/16 inch; 3/4 inch diameter bore tapered to match machine; 5/16 inch diameter orifice
Polyester	Reverse taper nozzle with 3/4 inch diameter bore tapered to match machine; 5/16 inch diameter orifice. Also, ball/seat/spring shutoff type nozzle with 1/4 inch diameter orifice
ABS	General purpose design with a 3/4 inch diameter bore tapered to match machine; 5/16 inch diameter orifice
Polyphenylene Oxide (noryl)	General purpose design with a 3/4 inch diameter bore tapered to match machine; 5/16 inch diameter bore
Polycarbonate Foam	Mechanical shutoff nozzle activated by movement of injection sled assembly; 1/4 inch diameter orifice
Nylon Foam	Mechanical shutoff nozzle activated by movement of injection sled assembly; 1/4 inch diameter orifice

Table 3

Constant mold temperatures were maintained at preset levels (anywhere between 60 and 210 F) by circulating water temperature control units. To obtain high quality parts, separate temperature controllers were used on each half of the mold. This arrangement can also keep parts from sticking in the stationary half of the mold.

Some Materials More Difficult

Molding problems encountered in the MM&T work were caused in part by the use of plunger machine. As noted, reciprocating screw machines are recommended for production applications. Other molding problems were related to specific materials.

Ployester—Shrouds were successfully molded using glass reinforced polyester (Valox), i.e., the molds filled properly and complete parts were produced. However, the parts did not have strong weld lines or good surface finish. Furthermore, parts were brittle and often cracked when ejected from the core by the stripper plate. All attempts to fill the mold faster through the use of hotter molds, shorter gate lands, larger gates, different nozzles, or a larger sprue failed to significantly improve part

Part	Material	Typical Weight (gm)	(oz)	Color	Moldability as Rated by Molder	Quality of Parts (Visual Examination)
Shroud	Nylon (43% GR)	519	18.30	Greenish white	Excellent	Good (slight warpage)
	ABS (40% GR)	529	18.65	Ivory	Good	Good (some sink marks)
	PPO (Noryl) (30% GR)	520	18.35	Medium gray	Excellent	Excellent (smooth, low shrinkage)
	Polyester (30% GR)	588	20.75	White	Fair to good	Poor (brittle, cracks easily)
	Polycarbonate (40% GR)	562	19.85	Light brown	Fair	Good (obvious weld lines, discolored)
	Polycarbonate (20% GR)	513	18.15	Very light brown	Fair to good	Very good (obvious weld lines)
	Polysulfone (40% GR)	To be supplied	To be supplied	Medium brown	Poor to fair	To be supplied
	Nylon/SAN (30% GR)	512	18.10	Black	Good	Fair (highly stressed, gates too large)
	Nylon Foam (30% GR)	832	29.40	Greenish gray	Good	Fair (large internal voids, heavy)
	Polycarbonate Foam (40% GR)	703	24.80	Brownish white	Excellent	Excellent (good foaming action)
Coilform	Nylon (43% GR)	164	5.79	Greenish white	Excellent	Good (slight warpage)
	ABS (40% GR)	162	5.72	Ivory	Excellent	Fair to good (pronounced sink marks)
	PPO (Noryl) (30% GR)	162	5.22	Medium gray	Excellent	Excellent (smooth, no sinks, low shrinkage)
	Polycarbonate (40% GR)	185	6.53	Light brown	Fair	Fair to good (much flash, significantly discolored)
	Polycarbonate (20% GR)	164	5.78	Very light brown	Fair to good	Good (much flash)
	Nylon/SAN (30% GR)	158	5.58	Black	Excellent	Very good (spotted surface)

Table 4

quality. Brittleness will probably be much less a problem, however, with a reciprocating screw machine.

Polycarbonate—Initially, the 40 percent glass reinforced polycarbonate caused numerous processing difficulties. These included incomplete fill, burning of material, part sticking, streaked parts, porous parts, and material contamination. These problems were overcome by enlarging the sprue and gates, increasing mold temperature, reducing land length, and incorporating small undercuts into the core of the shroud mold to prevent sticking. Lengthening the nozzle also provided significant process improvement. The resultant parts had moderately smooth surfaces and strong weld lines, although they were highly discolored with large brown and amber streaks and spots.

Polysulfone—A completely filled shroud was never produced using the plunger machine with 40 percent glass reinforced polysulfone. Basic shrouds were successfully molded on a reciprocating screw machine, however, once problems with sticking to the male core were overcome. Parts molded on the reciprocating screw machine showed excellent quality with good surface finish, strong weld lines, and only minor discoloration.

Foamed Nylon—The 30 percent glass reinforced nylon structural foam material was easily processed resulting in excellent surface finish, color, and dimensional control. However, poor foaming action resulted in excessively heavy parts containing large random bubbles. These problems were never satisfactorily solved due to constraints of the program schedule.

High-Quality Parts

Table 4 presents general characteristics of the injection molded parts. The highest quality parts and best moldability were obtained with nylon, ABS, polyphenylene oxide (noryl), and polycarbonate foam.

To further evaluate the materials and the design, shrouds and coilforms were assembled in various material combinations for temperature-humidity, temperature-shock, and vibration tests. There were no significant failures in this series of tests, although changes in color, surface texture, weight, and dimensions were observed in some materials after the temperature-humidity tests. These tests also served to substantiate short term durability of the glass reinforced thermoplastics.

TBE developed a manufacturing plan for high rate production of the plastic shroud and support structure. A part of this plan was a production sequence for injection molding which includes the procedures involved in obtaining an accurate, trouble free mold and in providing consistently high quality parts.

Part or Task	Cost Elements	Unit Cost ($) in Quantities of: 25,000	50,000	100,000
Shroud (1 required)	Part	4.35	4.35	4.35
	Tooling	0.20	0.10	0.05
	Machining	3.60	3.60	3.60
	Assembly (rings)	1.96	1.96	1.96
	Subtotal	10.11	10.01	9.96
Forward Ring (1 required)	Part	1.00	1.00	1.00
	Tooling	0.16	0.08	0.04
	Machining	0.90	0.90	0.90
	Subtotal	2.06	1.98	1.94
Aft Ring (1 required)	Part	1.35	1.35	1.35
	Tooling	0.04	0.02	0.01
	Machining	0.90	0.90	0.90
	Subtotal	2.29	2.27	2.26
PC Board Support Strips (3 required)	Extrusion	0.33	0.33	0.33
	Retainers	1.20	1.20	1.20
	Rivets	0.02	0.02	0.02
	Tooling	0.03	0.02	0.01
	Machining	4.95	4.95	4.95
	Assembly	0.90	0.90	0.90
	Subtotal	7.43	7.42	7.41
Assembly (support strips to rings)	Screws	0.54	0.54	0.54
	Tooling	0.03	0.02	0.01
	Assembly	0.60	0.60	0.60
	Subtotal	1.17	1.16	1.15
Chemical Coating	Labor	0.40	0.40	0.40
Total Cost of Subassembly		23.46	23.24	23.12

Table 5

Production Costs Compared

After sample parts were fabricated and testing was sufficiently complete to identify the necessary design changes, a study was performed to compare the production cost of the nonmetallic shroud and support structure with that of a similar subassembly fabricated from aluminum.

Table 5 shows the cost analysis for the aluminum shroud and support structure and Table 6 the analysis for a plastic shroud and support structure. Comparison of the two tables shows a cost reduction of well over 50 percent for the plastic assembly. If further analysis shows that the seeker electronics can withstand higher temperatures (up to 300 F), an all plastic shroud with molded in rather than aluminum strips, could be designed, reducing the production cost nearly 40 percent more to about $6.00.

Part or Task	Cost Elements	Unit Cost ($) in Quantities of: 25,000	50,000	100,000
Basic Shroud[(a)] (1 required)	Part	3.50	3.50	3.50
	Tooling	0.70	0.35	0.18
	Subtotal	4.20	3.85	3.68
PC Board Support Strips (3 required)	Extrusions	0.33	0.33	0.33
	Retainers	1.20	1.20	1.20
	Rivets	0.02	0.02	0.02
	Tooling	0.03	0.02	0.01
	Machining	1.20	1.20	1.20
	Assembly	0.90	0.90	0.90
	Subtotal	3.68	3.67	3.66
EMI Coating[(b)]	Material	1.27	1.27	1.27
	Tooling	0.12	0.06	0.03
	Labor	0.60	0.60	0.60
	Subtotal	1.99	1.93	1.90
Assembly	Labor	0.30	0.30	0.30
Total Cost of Subassembly		10.17	9.75	9.54

(a) The shroud cost shown is for 30 percent glass reinforced polyester, the most expensive sheet material. Costs ranged downward to $1.85 for 40 percent glass reinforced ABS.

(b) The EMI coating is required to provide a conduction shield for the seeker electronics that will reduce electromagnetic interference to acceptable levels.

Table 6

Computerized Designs Reduce Costs

Standardized Scales Increase Accuracy

NORMAN A. FORBES is a Senior Process and Development Engineer, Indiana Army Ammunition Plant, Charlestown, Indiana. Mr. Forbes received his bachelor's degree in electrical engineering from the University of Toronto in 1956 and his master's degree in electrical engineering from the University of Louisville in 1969. He is the holder of 11 patents. Prior to assuming his present duties, Mr. Forbes was associated with American Standard, Inc., and Westinghouse Electric Corp. His published articles include an AIEE conference paper and a chapter in Diode Source Book (Cowan Publishing Corp., 1961). He presently is involved in developing a computerized materials handling system for Load, Assembly, and Pack (LAP) propellants.

A program of scale standardization begun at the Indiana Army Ammunition Plant(INAAP) has to date resulted in $433,000 in savings, and additional savings are expected. Scale accuracy has been improved 50 percent, and the new scales are less likely to become obsolete. Other indirect benefits include less maintenance time, shorter setup time, less "down" time, and a reduced spare parts inventory. Comparable savings for standardized scales at other defense ammunition plants are projected.

The scale standardization program began at INAAP in December, 1977. The effort was divided into two phases: Phase One, Engineering Study; and Phase Two, Hardware Procurement. Although Phase Two is not yet complete, the savings in capital expenditures have already reached 190 percent of investment.

Scale Standardization Needed

By 1977, the Indiana Army Ammunition Plant had nearly 2000 scales used in support of Load, Assemble, and Pack (LAP) work. Most of these were simple bench models used by quality assurance inspectors. Approximately 100 were either automatic checkweigher scales or complex netweigher/checkweigher scales that are used to weigh out accurate quantities of propellant.

Due to modernization programs, INAAP had systematically planned to bring new and modernized facilities onto assembly lines; any existing scales were scheduled to be replaced or updated. About 100 new scales were comtemplated, reflecting the latest in available control technology. The complexity of existing maintenance problems, however, would be increased.

NOTE: This manufacturing technology project that was conducted by the Indiana Army Ammunition Plant was funded by the U.S. Army Munitions Production Base Modernization Agency under the overall direction of the U.S. Army Office of Manufacturing Technology, DARCOM. The MPBMA Project Engineer is Norman A. Forbes (812)282-8961.

Standardization of all scales was the ideal solution. Plant maintenance personnel would be faced with one technology and one set of problems, instead of many.

At INAAP, no single project manager or department head had the resources or the personnel to standardize scales. Unless some management action was taken, scales would continue to be procured piecemeal, with little or no effort to coordinate procurement with the needs of other projects or departments. Clearly, a unified effort with management coordination was mandatory.

Choosing a Technology

Before the formal standardization program was commenced, a study was made outlining the technical options for management. Table 1 indicates how the four competing technologies (fluidic, analog electronic, digital electronic, and computer) were compared and rated. A qualitative rating was assigned to each technology for each of five characteristics (initial cost, spare parts cost, maintenance, accuracy, and obsolescence). Except for the computerized scales, technical arguments supporting the ratings were based on considerable practical experience.

Four major conclusions were drawn from the report and subsequent analyses:

(1) Although a few fluidic scales did exist, they had several drawbacks: the fluidic transducer was no longer manufactured, the scales had poor stability, and maintenance skills were difficult to master.

(2) Among electronic scales, digital scales were invariably superior to analog scales in accuracy, speed, and tolerance of propellant buildup on the flexures.

(3) Computerized scales possessed all the advantages of digital scales and were less likely to become obsolete. Most important, they cost less.

(4) The techniques of maintaining computerized scales were unfamiliar to existing maintenance personnel. Consequently, supplementary training would be necessary.

Coincidentally, the final decision to standardize on computer scales was strengthened by the fact that a major scale vendor, Hi—Speed Checkweigher Company, had independently decided to embark upon an in-house scale standardization program, using computerized scales to achieve a modular, high performance, flexible system.

Defining Modular System Goals

Once the technology was determined, the primary objective of scale standardization became the development of a cost effective modular control system that would meet all present and future scale needs at INAAP (Figure 1). The following additional goals were written into the new scale specifications:

- Improve the scale setup characteristics. Provide readouts at the scale itself, so that one technician instead of two could perform scale setup.
- Improve the man-machine interface on the scale displays, providing the technician with diagnostic aids and panel displays to help him find troubles quickly. If the setup has been done incorrectly or if there is some hardware failure, the scale will stop and display a coded message identifying the nature of the problem.

	FLUIDIC	ANALOG	DIGITAL	COMPUTER
INITIAL COST	P	G	F	E
SPARE PARTS COST	P	G	F	E
MAINTENANCE COST	P	F	G	G
ACCURACY	P	G	E	E
OBSOLESCENCE	P	F	F	E
E = EXCELLENT G = GOOD F = FAIR P = POOR				

Table 1

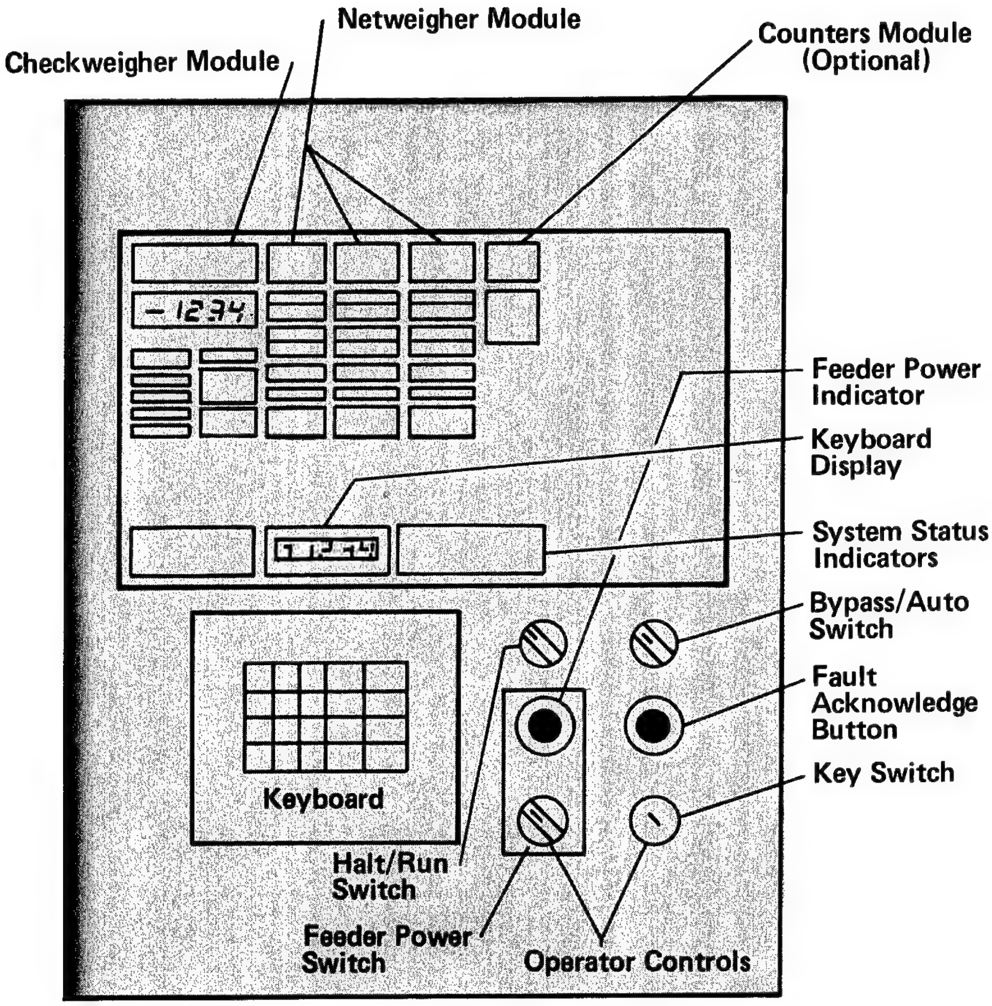


Figure 1

- Provide modular packaging for the controls, so that board changing and board repair would be simplified to the maximum extent possible.
- Improve the reliability, speed, and accuracy of the scales through maximum use of microprocessor technology.

Effects of Scale Standardization

All new scales at INAAP have been converted to the modular system. The netweigher and checkweigher functions are achieved through a combination of six different circuit boards. Four boards do most of the work; the remaining two contain the front panel display and the battery backup—both relatively simple functions. Controls for different scales differ only in the programs stored in circuit board memories and in the position of certain switches and jumpers. Additionally, old scales can be updated by being fitted with computerized controls.

Standardization applied only to the scale controls. It was quickly recognized that very little of the scale mechanisms (as distinct from the controls) could be stand-

ardized, due to their great variety. Scales in use at INAAP range from massive devices nearly 10 feet high used to weigh 35 lb propellant charges for 155mm weapons to smaller scales which weigh 25 gram (0.055 lb) mortar charges

To retain modular circuits, the front panel displays plug into the printed circuit boards and therefore can be specified with any desired lights or indicators without loss of modularity. Also, the system will accept any of the vendor's standard commercial modules, such as counters, statistics, histograms, printer drive, and sorting. Use of customized modules made up of modular circuit boards reduces the cost of specialized functions, especially since all modules in an enclosure have a common bus and communicate readily with each other.

Scale setup is now accomplished in less time than under the previous systems and requires one person instead of two. In a munitions plant the scale itself is normally located in an explosive environment, and the control is necessarily located in a nonexplosive area some distance away. To set up the standardized scale, the technican sets time and weight limits by means of the keyboard at the control. Then he goes to the scale to check for hysteresis and binding and to adjust the feeders. A compact display panel at the scale gives him all the information he needs to make these adjustments; formerly, two men with walkie-talkies were needed.

Scale standardization achieved a cost savings in scales for 155mm charges. The largest of these charges weighs 35 pounds and requires five consecutive dumps. The need for a multiple dump feature, including the ability to sum the five weights, was identified during the early scale standardization surveys; as a result, the number of dumps is a simple keyboard entry. Without a scale standardization program, the 155mm scales undoubtedly would have required a special developmental effort.

Scales Faster, More Accurate

Computerized scales are faster and more accurate and reliable than earlier generation scales. The speed (number of weighings per minute) of netweigher/checkweigher models has been increased by 10 percent. Formerly, following a prolonged shutdown, scale stability was uncertain; the scale required the attention of a technician. With the new models, if the setup has been done correctly good charges will be weighed out within a few minutes of turn on, with no help from the technician.

As we have stated, computerized scales are substantially more accurate than the analog scales used at INAAP. Table 2 lists the measured accuracies of scales under the new system. Although it is too soon to measure reliability, the reduced parts count of the computerized scales would logically lead to improvement in this area as well.

Working closely with the Hi—Speed Checkweigher Company, especially in the review of scale specifications, has been very beneficial. Discussions usually identified unreasonable costs. For example, in theory it would be permissible to specify a front panel light to monitor any function in the scale, but in practice it proved much less expensive if displays were restricted to signals that were generated in the boards to which the front panel was directly connected.

A good relationship also developed between departments at INAAP during the scale standardization program. Maintenance personnel reviewed proposed panel layouts and suggested improvements in panel displays; Quality Assurance and Plant Engineering personnel insisted on the one technician setup;and Industrial Relations personnel provided facilities for courses on computer technology for technicians.

Finally, costs were greatly reduced (see Table 3). According to current projections, the scales already procured would have cost significantly more had each been a separate design effort. Each additional scale purchased under the scale standardization program will save additional money. The benefits of this program apply also to other ammunition plants; for example, the Iowa Army Ammunition Plant recently purchased a computerized scale as noted in Table 3.

A Review of Scale Technology

Scale controls have other complexities. Even before the scale output is read, enough settle time must be allowed for the mechanism to come to a rest. Additionally, the small voltage from the scale transducer must be filtered and amplified, and then fed to decision-making logic circuits. For digital scales, part of the signal processing involves passing the amplified and filtered transducer voltage through an analog—to—digital (A/D) converter. This is one of the outstanding advantages of digital technology: the A/D converter is capable of much

Checkweigher Scales (Type T-59) for 60/81MM Mortar Charges:	
Scale A	0.086 grains
Scale B	0.132 grains
Scale C	0.073 grains
Scale D	0.110 grains
Specified Accuracy:	0.15 grains
Netweigher Scales (Type X-174) for 60/81MM Mortar Charges:	
Scale A	0.056 grains
Scale B	0.040 grains
Scale C	0.017 grains
Scale D	0.123 grains
Specified Accuracy:	0.15 grains
Checkweigher Scales (Type T-59) for 105MM Charges:	
Scale A	1.85 milliounces
Scale B	2.77 milliounces
Scale C	2.63 milliounces
Scale D	2.09 milliounces
Scale E	1.82 milliounces
Scale F	2.27 milliounces
Scale G	2.94 milliounces
Scale H	2.50 milliounces
Specified Accuracy:	3.5 milliounces

Table 2

greater accuracy than the analog circuits. A scale is basically a material handling mechanism plus a control. In a simple bench scale, the mechanism is simply the scale's weighing apparatus. Material handling consists of placing the commodity to be weighed on the scale pan and then removing it. In a more complex scale, such as might be built into an automated manufacturing process, the scale's mechanism must cope with a variety of material handling tasks. Some of the common tasks are listed in Table 4.

The scales at INAAP use a spring—flexure—dashpot—transducer system in the weighing mechanism. The functions of these components are as follows:

- The **spring** supports the scale pan. Over a small range, there is a straight line relationship between the weight on the scale pan and the downward movement of the scale pan.
- The **flexure** forces the scale pan to follow a fixed path, so that the dashpot and transducer remain centered and do not bind.
- The **dashpot** supplies critical damping, so that the scale comes to rest as quickly as possible after a weight has been added to it.
- The **transducer**, which converts motion to voltage, responds to small movements of the scale. The electronic transducers used in recently-purchased scales at INAAP are invariably of the Direct Current Differential Transformer (DCDT) type. Other transducers can be used,but they must be approved for use in Class II dusts.

Additionally, a tare weight is added to the scale and calibrated so that the scale transducer output is approximately zero volts when the required commodity weight is added to the scale pan.

This description of scale details and control functions is a convenient way to review the problems facing the scale technician. Regardless of the technology used in a particular scale, the technician is faced with a number of basic tasks that are common to all scales. The technician's first job is to center the dashpot and the transducer so that neither of them bind; he must also adjust the transducer so that the boltage in the middle of its sensitive range is zero.

During scale set-up, the technician must perform additional tasks. One of these tasks is adjusting the settle times. Another task is to set the upper and lower weight limits, so that the scale control can make a logic decision as to whether the measured weight is between these limits.

Although set-up tasks may be basic, different scale technologies require different skills. The following examples show how changing the technology changes the task of adjusting the settle time:

	Type of Scale	Previous Control	Standardized Control	Net Savings	Number of Scales	Total Savings
1.	X-170-105mm	$23,000	$11,000	$12,000	21	$252,000
2.	T-59-105mm	6,200	4,700	1,500	14	21,000
3.	105mm-BW&T	6,700	5,200	1,500	14	21,000
4.	X-170-155mm/8"	17,500	9,500	8,000	6	48,000
5.	X-174-60/81mm	12,000	8,000	4,000	4	16,000
6.	T-59 60/81mm	6,200	4,700	1,500	2	3,000
7.	X-170-155mm/8" (Center Core)	23,000	11,000	12,000	1	12,000
8.	X-165 Replacements	17,500	9,500	8,000	7	56,000
9.	X-170, Iowa AAP	12,000	8,000	4,000	1	4,000
						$433,000

Table 3

LOAD:	Placing a commodity on the scale.
SETTLE TIME:	The time needed for scale pan to come to rest following a LOAD operation.
WEIGH:	Measuring the small difference between the calibration weight and the commodity weight.
LOGIC DECISIONS:	Making accept/reject decisions on the basis of weight comparisons.
FEEDBACK:	Altering a scale's set-point on the basis of errors measured downstream of the scale.
UNLOAD:	Removing a commodity from the scale.
CYCLE:	Moving the scale from task to task.
DISPLAY:	A man-machine interface that enables the operator to monitor scale performance.
DATA TRANSFER:	Transmission of weight and logic data to some remote processor or display panel.

Table 4

- For a fluidic scale, a needle valve is adjusted, thereby changing the flow of air into a reservoir (fluidic capacitor). The technician observes the resulting time delay by means of fluidic panel indicators.
- For an analog electronic scale, a potentiometer, usually soldered to one of the printed circuit boards in the scale control, is adjusted with a screwdriver. The resulting delay is then observed using an oscilloscope or pilot light.
- For a digital scale, the required time is set on a thumbwheel switch, usually located on the front panel of the scale control.
- For a computerized scale, the keyboard on the front panel of the scale control is used. By entering the appropriate codes, the timer circuit is "addressed" and the desired time is entered, all with the same keyboard. The scale's operating manual provides instructions for these entries.

There is more to a basic scale task than simply making an adjustment. The technician must become familiar with the entire technology. He must learn to recognize when the results of his adjustments are erratic or incorrect. Each type of technology had its own peculiarities and pitfalls. For example, in the ten-turn potentiometer used to adjust settle time in an analog circuit, the sliding contact can fall off its lead screw. The technician must learn to recognize that turning the potentiometer no longer changes the settle time. By itself, this problem is not difficult. But each scale technology has many such problems the sum of which is significant, and requires a specific body of knowledge and learning effort by the technician. Therefore, compounding scale technology within a plant tends to complicate maintenance and operating problems.

Prototype Machine Shows 50% Savings

New Concept in Electronic Component Insertion

Efforts at Martin Marietta under U. S. Army Missile Command sponsorship have resulted in a promising new concept for inserting electronic components with leads into printed wiring boards. The new technique for mechanical insertion reduces the time required for this extremely tedious operation by about 85 percent. As a result, manufacturing costs can be reduced by 50 percent or more, a conservative figure based on work with a prototype machine. A production machine would be faster, and improvements in present manual loading are possible to provide further substantial savings.

After first determining that modification of existing techniques would not significantly improve productivity, Martin Marietta's investigators developed an entirely new concept for component insertion. Based on a device called a LOCASERT (location and insertion), the concept addresses all kinds of insertion for electronic and electrical components. Originally designed for components with nonaxial leads, it appears to be equally cost effective with those of axial design. This universality of approach should help to ensure broad application in electronics manufacture.

Multifunction Component

The LOCASERT is an injection molded part that functions as an electrical insulator, thermal insulator, lead positioner, handling base for the insertion machine, and component spacer. Although LOCASERTs can be used to reduce manual insertion time as well, an integral part of the program was development of a machine for automatic insertion. Maximum savings are, of course, associated with machine insertion.

ROBERT L. BROWN is a General Engineer at the U. S. Army Missile Command in Huntsville, Alabama. His current projects involve creative direction of contractor engineers on projects such as the fully additive manufacture of printed wiring boards (Hughes), ultraviolet curing of conformal coatings for PC boards (Hughes), product cleanliness techniques for PC boards (Martin-Marietta), laser scan testing of PC boards (Chrysler), rigidflex assemblies (McDonnell-Douglas), and insertion of nonaxial lead devices in locaserts (Martin-Marietta), a recent approved success. A Registered Professional Engineer in Alabama and holder of a B.S. in Metallurgy (1958) from Alabama University, Mr. Brown holds six patents and is author of fifteen technical briefs which NASA rates as equivalencies to patents. He was the first recipient of the NASA "Noteworthy Contribution" award in 1970 for his many contributions to their technical utilization program, and patented several inventions that were used in production. While employed by Chicago Bridge and Iron in 1948 he invented an early television X-ray imaging system, which was the first such system to reach broadcast resolution and was the basis of an X-ray television system built by Zenith Corp. and delivered to Marshall Space Flight Center in 1972. This system was used at Vanderbilt University as the best available nuclear medical imaging system and is still in use there as a television X-ray system. His most recent development of an X-ray imaging system is characterized by revolutionary increases in resolution and performance through use of fiber optic technology, in which 80-100% of the radiation is captured in the image and resolution is more than 20 lines per inch, with increases easily possible through use of finer fibers. Also while at Chicago Bridge and Iron he patented a method for brazing claddings on dissimilar metals which was widely used commercially for many years. A member of the International Society of Microelectronics, Mr. Brown worked as an aeronautical engineer during World War II at Birmingham and also worked as an engineer with the Birmingham Fabrication Company.

NOTE: This manufacturing technology project that was conducted by Martin Marietta was funded by the U.S. Army Missile Command under the overall direction of the U.S. Army Office of Manufacturing Technology, DARCOM. The MICOM Point of Contact is Mr. Bobby Austin (205)876-8445.

The Martin Marietta study addressed three component families—pin through hybrid packages, dual in line packages, and TO type sealed packages—as illustrated in Figures 1 to 3. Insertion of such components into printed wiring boards is difficult because the leads are long, unstable, and often bent in different directions. As one can see in Figure 4, which shows attempted manual insertion of a hybrid package, trial and error attempts to allign pins with holes can be very time consuming and frustrating.

Facilitates Insertion

Applying the new concept, these problems are overcome by loading the component into a LOCASERT before assembly to the wiring board. Typical LOCASERT designs are shown in Figure 5. Figure 6 shows a dual in line package loaded in a LOCASERT. Loading into the LOCASERT is facilitated by cone shaped funnels that lead into short cylindrical holes whose diameters exceed those of the wire leads. This design is illustrated in Figure 7. As shown, bent wires are guided into their proper locations. The lead wire ends are inserted so they are flush with the bottom surface of the LOCASERT. Any protrusion could create further bending problems that would interfere with later insertion into the wiring board.

The detents or recesses on each end of these devices provide for position location on the wiring board. Transverse distance between these detents (i.e., the distance between the two recesses on the same end) is common for all LOCASERTs regardless of size. This distance

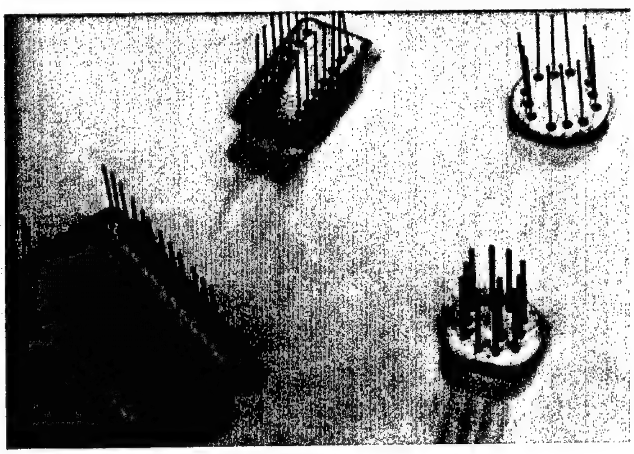


Figure 1

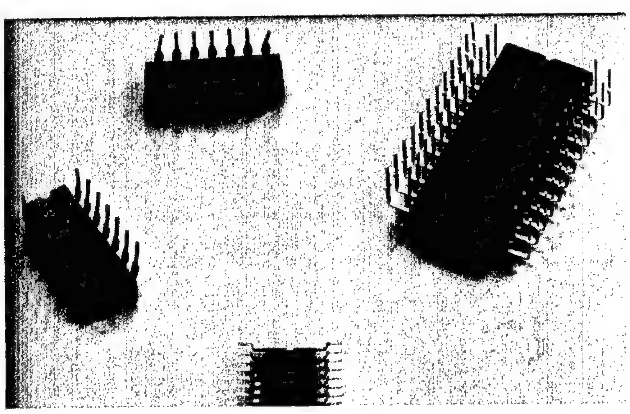


Figure 2

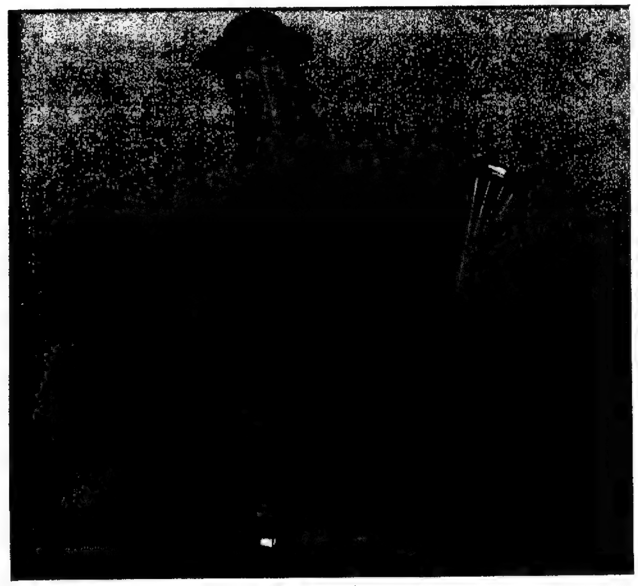


Figure 3

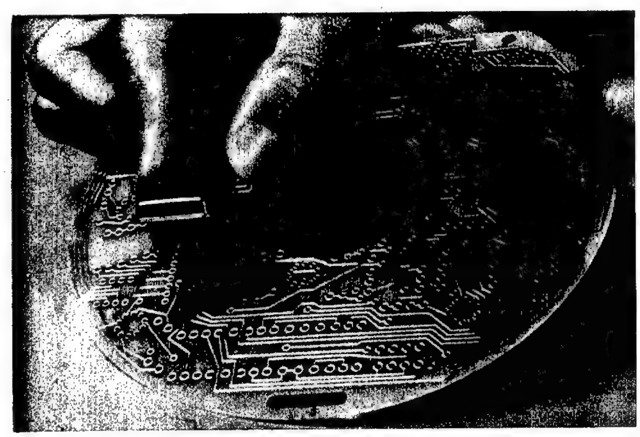


Figure 4

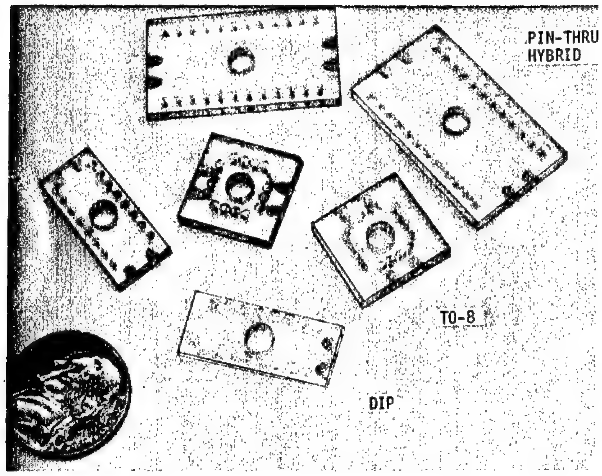


Figure 5

Figure 6

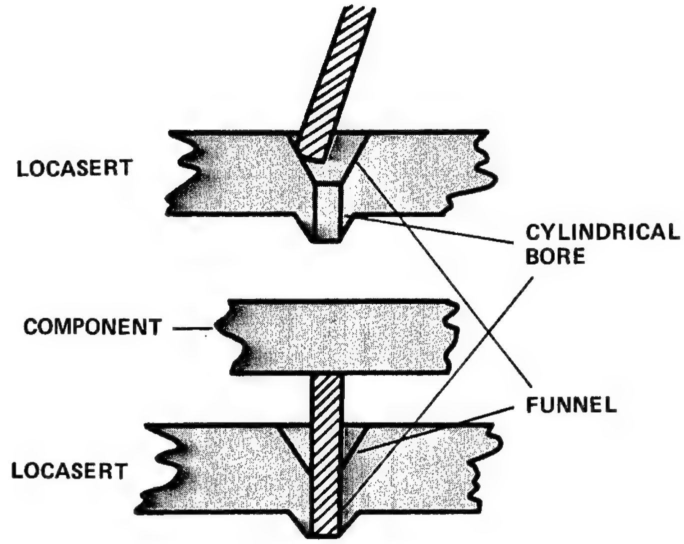


Figure 7

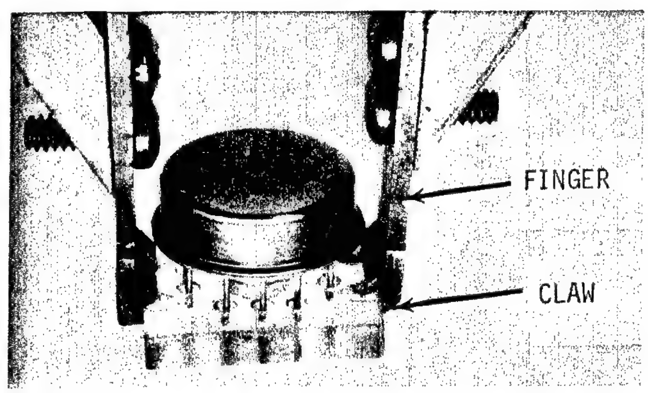


Figure 8

matches the distance between the fingers and claws on the insertion machine (see Figure 8) that grip the LOCASERTs. As seen in Figure 9, the detents define the intersection of the X-Y axis on the LOCASERT, called the zero intercept. This is coincident with a like zero point on the printed board, which is aligned under the insertion head axis line. With these three points in line, accurate placement of the device for insertion is ensured. Thus, a single set of fingers and claws—which automatically adjust to differences in length of the LOCASERT—can be used to accurately position all sizes of LOCASERTs to a board.

When properly aligned by this "zero home" concept, holes in the LOCASERT each are filled with a lead wire and are positioned directly over counterpart holes in the printed board. The wires then are guided into the board holes by lowering the insertion head to bottom the component against the LOCASERT.

Machine Operation

The prototype machine used for insertion is shown in Figure 10 with its covers removed. Loaded LOCASERTs are stacked in a magazine from which they are dispensed one at a time into a transport slide. The slide positions the LOCASERT into a pickup registry. The gripper assembly

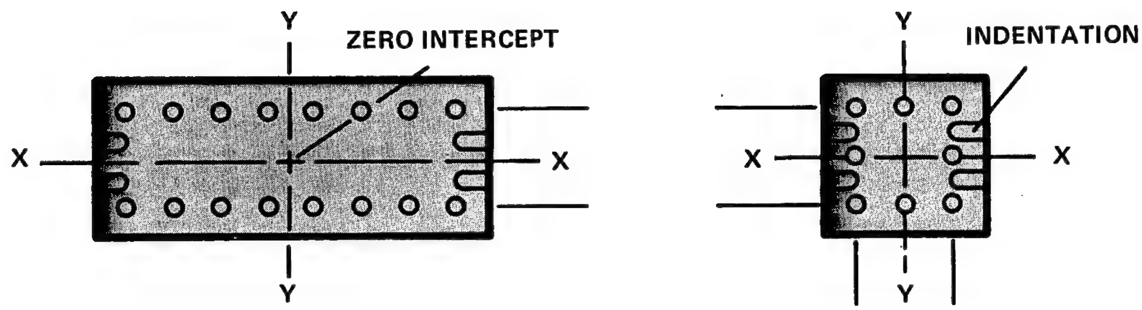


Figure 9

(fingers and claws) removes the LOCASERT from the registry and positions it close to the printed wiring board, which is precisely located under the insertion head. Location of the board is accomplished with an X-Y table, a template, and tooling holes in the board. Insertion then is accomplished as described above and the LOCASERT becomes an integral part of the assembly. During the insertion phase, the leads first are moved into the holes on the board and the gripper claws then are removed before the component is fully seated. The board and template can be repositioned on the X-Y table for insertion of successive components.

Substantial Savings

Simulated production runs were made for boards containing five components. Based on these runs, a cost analysis was performed indicating the tremendous cost saving potential of the concept. Results of that analysis show that manual assembly of five components to the board takes 7.18 minutes, totalling an assembly cost of $3.52 per board. The estimated cost of machine insertion is $1.73 per board, a cost reduction of better than 50 percent.

Potential production savings are considerably greater than that, however. Manual loading of the components in the LOCASERTs accounts for $1.16 or 67 percent of the machine insertion cost. Actual machine time is only 1.01 minutes per board, a cost of just $.52 (the remaining 5 cents is in tooling setup). Thus, development of a machine to service and load components into the LOCASERTs would provide substantial additional savings. Furthermore, a production machine for insertion would be considerably faster than the prototype machine. The estimated cost of actual machine time on a production machine is just 25 cents. With further development of the concept, including machine loading, full scale production costs are foreseeable that are another 50 percent under those for the simulated run on prototype equipment.

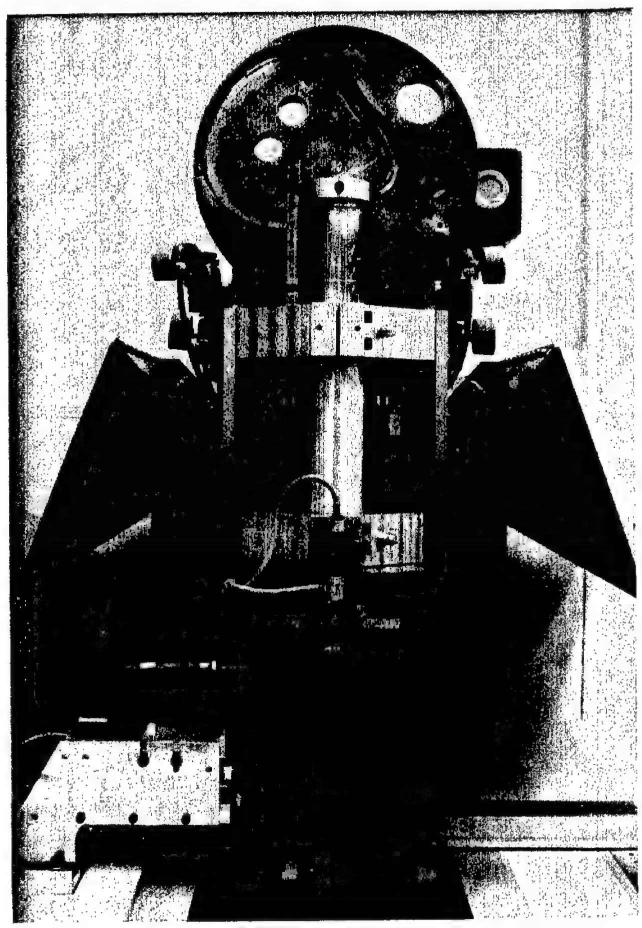


Figure 10

The estimated cost of an insertion machine is $35,000, which could be amortized over the production of about 100,000 components based on the prototype cost analysis. This figure, too, will decrease as further cost savings are realized.

Spraying Yields Straight Forgings

Cannon Tubes Horizontally Quenched

Mantech work at Benet Weapons Laboratory, Watervliet Arsenal, has demonstrated that horizontal spray quenching can replace vertical immersion quenching for heat treatment of gun tube forgings, allowing uniform cooling over the tube length. As a result, greater uniformity in tube microstructure and mechanical properties is obtained. The process could be implemented easily by any gun tube forger. It should also be adaptable to other large tubular forgings and should provide the same basic benefits in these other cases.

Horizontal Immersion Quench

Forgers have generally felt that long, tubular products must be quenched in a vertical position in order to minimize permanent deflections that require extensive straightening, machining, and stress relief operations. There have also been claims that vertical heating provides greater temperature accuracy and uniformity (Ref. l). Such thinking began to change in 1972 when Curtiss-Wright Corporation conducted a feasibility study (Ref. 2) on horizontal quenching. They concluded that—using proper procedures—horizontal quenching can produce acceptable properties in gun tubes without severely distorting the tubes. Their work involved immersion quenching—i.e., plunging the forging into a body of quenching fluid.

However, uniform quenching is difficult to obtain with this immersion process. To understand why, consider that there are three commonly recognized stages of an immersion quench operation (Ref. 3). At first, a continuous vapor blanket envelops the entire surface (Stage 1). Heat is transferred by radiation and conduction through this vapor to the vapor-liquid interface. In Stage 2, vapor is carried away by gravity and convection, causing breaks in the blanket. Where these breaks occur, the surface of the forging is wetted by the quenching fluid, which in turn vaporizes and reforms the vapor blanket. In Stage 3, the forging surface becomes cool enough to be completely wet and is rapidly cooled by conduction to the quenching medium.

A severe quench (rapid removal of heat) is required for full hardening of lean alloy steels. To achieve this, third stage quenching must be reached as quickly as possible after immersion. This is done by rapidly agitating the forging in the quench medium to minimize or eliminate heat transfer through the vapor film. However, such agitation is difficult for shapes such as gun tubes. A common technique is to use propellers or water jets to create turbulence in the quench medium. While more

PETER V. DEMBOWSKI, formerly a metallurgist at the Benet Weapons Laboratory, currently is Manager, Metal Products Engineering, Lamp Glass and Components Department, General Electric Company, Cleveland, Ohio. Mr. Dembowski graduated from the Polytechnic Institute of Brooklyn and is Past Chairman of the Eastern New York Chapter of ASM. He has authored numerous technical articles in metallurgical journals.

NOTE: This manufacturing technology project that was conducted by the Benet Weapons Laboratory was funded by the U.S. Army Material Readiness Command under the overall direction of the U.S. Army Office of Manufacturing Technology, DARCOM. The ARRCOM Point of Contact is Dr. Fran Heiser (518)266-5507.

rapid quenching is obtained, the agitation is uncontrolled and pockets of steam or nonuniform cooling can occur over the length of the forging.

Spray Quenching An Answer

Spray quenching—the utilization of a continuous or intermittent water spray—is an alternative to immersion. Use of a high pressure water spray eliminates—or at least greatly decreases—Stage 1 and accelerates Stage 2 as spray impinges on the surface to mechanically break up the vapor blanket. With water spray, heat transfer coefficients are ten to fifteen times higher than for cooling in a circulated water bath. Heat flow is twenty to twenty-five times as great in the pearlite transformation region and nine to twelve times as great in the martensitic transformation range (Ref. 4).

With this background, an investigation of horizontal spray quenching of thick walled gun tube forgings was undertaken at the Benet Weapons Laboratory. The program involved three parallel efforts. The first was the construction and use of a small in-house facility to austenitize sections of gun tube forgings up to forty inches in length to temperatures up to 1800 F and then quench the section by either immersion or spray quenching. The second effort was to process a series of gun tube forgings on a continuous in-line furnace with an integral, wrap-around spray quenching system. The facility at Drilco Corporation in Houston, Texas, was used. Finally, two forgings with various wall thicknesses representative of several current forgings were heat treated using current practice with the exception that spray quenching was used instead of immersion quenching.

Bore Quenching Helps

Using the in-house spray quench facility, typical cooling rates were determined for several large cylinders. There was a significant difference in cooling rate when a bore quench was used. For the same specimen, surface cooling rate almost doubled (from 19,300 to 38,000 F/min) with the addition of a bore quench. Since the system was operated at the highest delivery pressure, the addition of a bore quench dropped the pressure and flow rate through each nozzle.

Discussions with designers of spray quench systems indicate that the lower pressure may have contributed to the wetting ability of the quench. Sprays that impact at high pressure appear to "bounce" off the hot surface of the forging, reducing the volume of coolant available to remove heat. Lowering the pressure results in better contact, with optimum contact occurring when the water pressure (drop velocity) is just sufficient to penetrate the vapor blanket and wet the surface.

In the Benet investigations, specimens with approximately two inch thick walls (comparable to the M68 breech configuration) were quenched to below 400 F at the mid-wall in three to six minutes, depending on the volume and pressure of the spray.

Processing At Drilco

A number of gun tube forgings in two series were processed at Drilco Corporation. The first series consisted of five M68 tubes (either scrapped for machining defects or condemned for reaching the set firing life) and two as-forged M137 rotary forgings. A second series consisting of one M68 tube and one M185 rotary forging was processed after mechanical properties of tubes in the first series were evaluated.

These forgings were processed on a Selas system consisting of a 64 foot long austenitizing barrel furnace, a 25 foot long high pressure/low pressure spray quench unit, a 64 foot long tempering furnace, and a 25 foot long spray quench. Forgings move continuously through this system on skewed rollers that also rotate them about their axes. The system was designed to process material of uniform cross section at a constant velocity with heating and cooling sequences adjusted for a constant production rate.

Temperature Gradients Monitored

The Drilco austenitizing furnace has five zones. Temperature heads in the first three zones rapidly heat the forging, while a lower holding temperature in the last two zones allows it to soak (achieve a uniform temperature across the cross section) before being quenched. Quenching is performed by a series of spray rings. The first ring sprays water at 30 psi to immediately lower the forging surface temperature. The subsequent rings, set at 8 psi, gradually but continually remove additional heat from the forging surface.

Temperature is monitored in dummy zones between furnace Zones 3 and 4 and upon exit from Zone 5. Temperatures measured on tubes in the first series are shown in Table 1. All tubes were cool to the touch at the muzzle as they exited from the austenitizing quench. One tube of each type was cut in half after processing and given an additional temper in a pit furnace to make sure that an adequate temper was obtained.

In this system, tube temperature is controlled by a combination of furnace zone temperature and the rate

Tube Type	Sequence No.	Max Temp., F (Dummy Zone)	Max Temp., F (Zone 5)
105mm M68	1	2010	1720
105mm M68	2	2070	1790
105mm M68	3	2100	1770
105mm M68	4	2120	1830
105mm M68	5	2150	1800
105mm M137	6	1950	1730
105mm M137	7	1950	1730
Temperature just before quench – 1650-1625 F			

Table 1

at which the tube moves through the zone. The high temperatures in the first series caused concern as they were detected, but alteration of a processing sequence was not permitted once it had been set.

Properties Measured

The processed tubes exhibited remarkable uniformity of hardness along their length—readings varied from 477 to 444 Brinell. Hardness across the wall thickness was 58 ± 1 Rockwell (610-640 Brinell). These measurements were taken in a radial direction on discs cut for mechanical property evaluation. The uniformity of hardness readings was not expected because of the heating differentials cited previously. The result indicates that **variations in hardness result more from quenching practice than from heating practice.**

Mechanical properties for individual tubes are shown in Figures 1, 2, and 3. While strength and also percent reduction in area were within specifications, impact energy at -40 F was far below what would be expected. Pit tempering had no obvious effect on toughness. To determine if the overheating during austenitizing was responsible for the observed properties, a short investigation of austenitization temperature was conducted on a typical gun steel material. The results are shown in Table 2. As seen, austenitizing temperatures above 1600 F resulted in much poorer impact strength. Based on this result and some previous work on soaking times (Ref. 5), the poor impact strengths of the first series were attributed to overheating.

For the second series of rotary forged tubes, furnace zone temperatures were set so that 1600 F would not be exceeded. The surface temperatures of both the M185 and M68 forgings were at least 1500 F but less than 1600 F as they left Zone 5. Properties for specimens from this series are shown in Table 3. Impact strengths were not significantly improved.

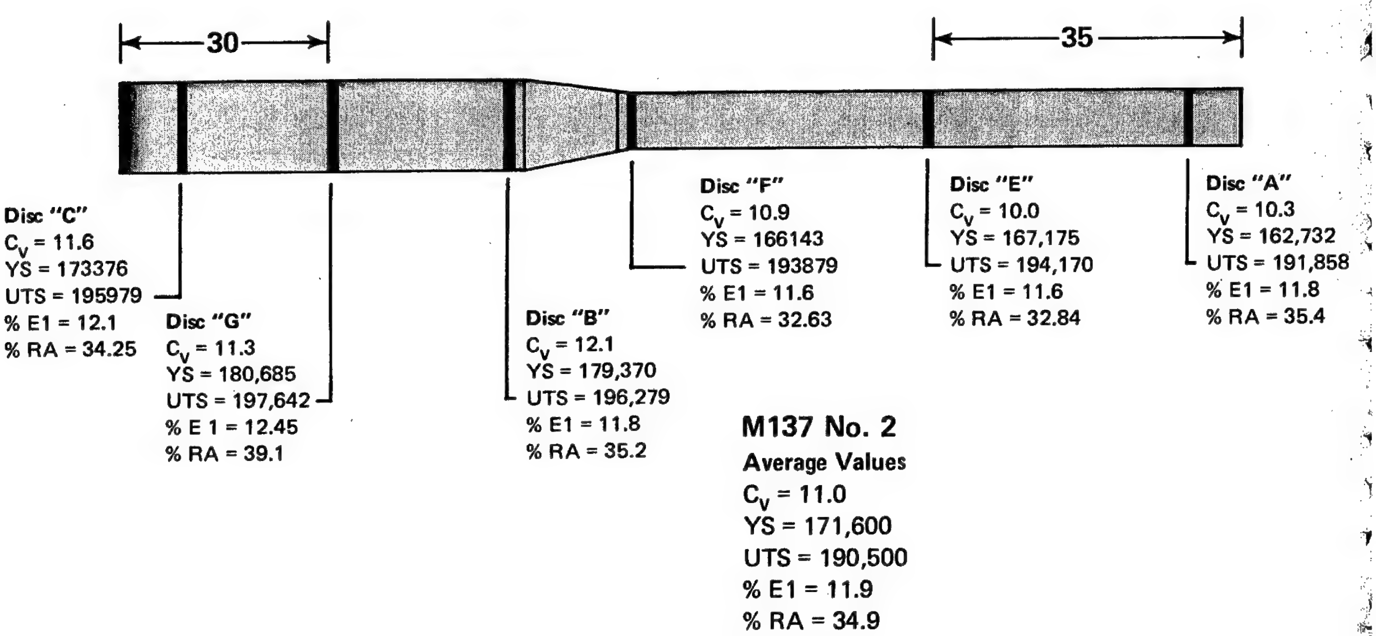


Figure 1

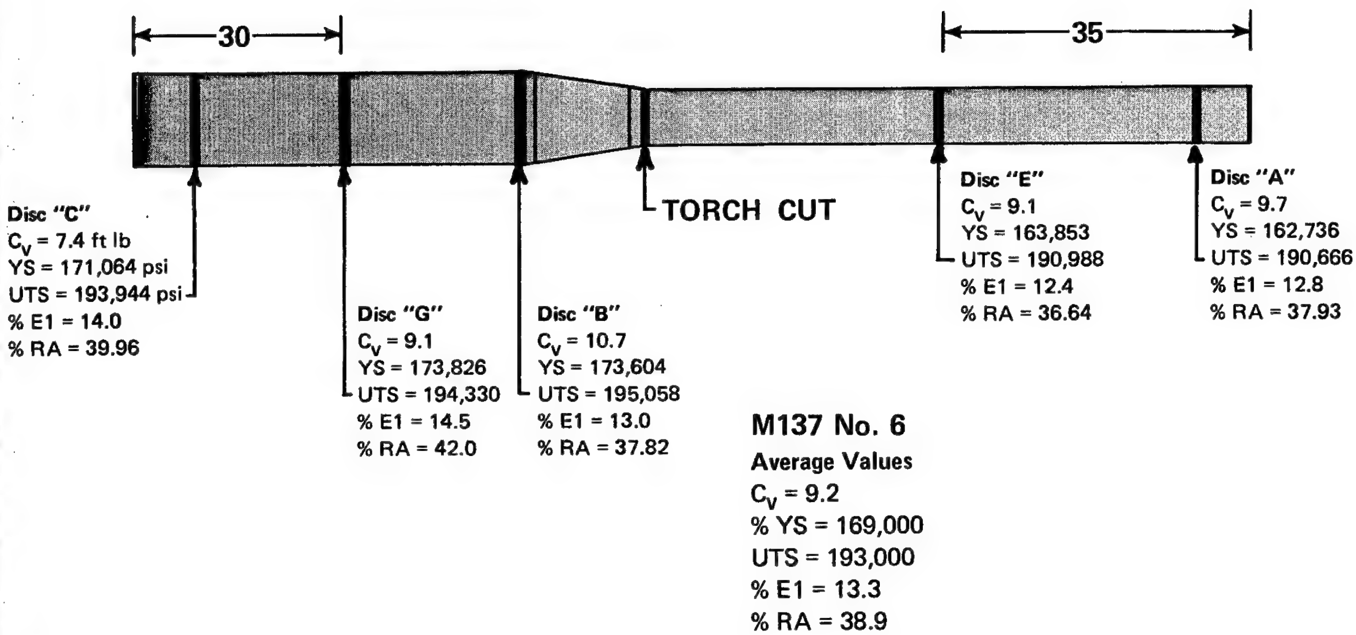


Figure 2

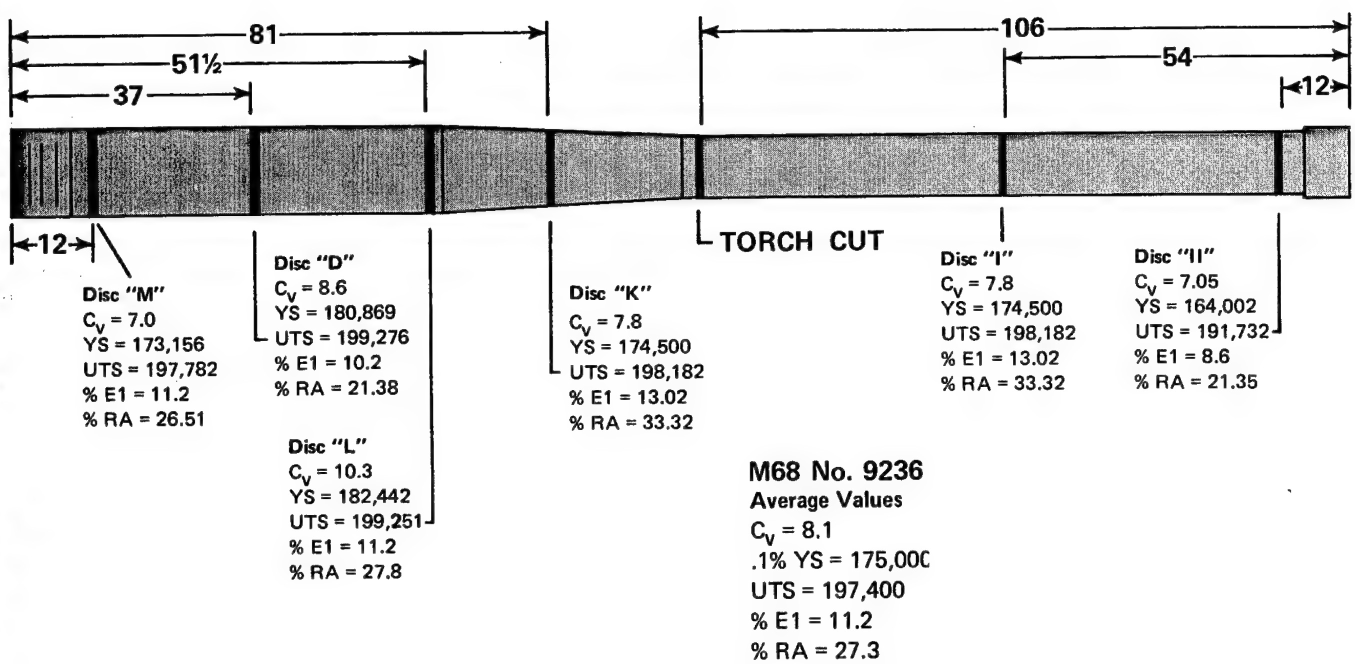


Figure 3

Austenitization Temperature, F	Yield Strength, ksi	Reduction in Area, %	Impact Strength, Ft-lb (-40 F)
1550	168	54	39
1600	168	48	32
1650	168	47	16
1700	166	49	17
1750	165	53	15
1900	163	45	13
2000	160	49	15

Table 2

Impact Strength, Ft-lb (-40 F)	0.1% Yield Strength, ksi	Ultimate Tensile Strength, ksi	Elongation, %	Reduction in Area, %	Comment
9.8	196	227	8.6	26.4	M68 breech as processed
10.0	196	226	10.0	33.1	M68 breech + 1070F 3 hr temper
11.0	177	202	10.7	27.6	M68 muzzle as processed
10.5	178	204	9.0	16.6	M68 muzzle + 1070F 3 hr temper
11.5	186	214	11.8	37.0	M185 breech as processed
11.0	189	214	10.4	31.8	M185 breech + 1070F 3 hr temper
10.6	177	207	12.1	30.6	M185 muzzle as processed
10.0	180	207	12.5	33.4	M185 muzzle + 1070F 3 hr temper

Table 3

Excellent Straightness, But Impractical

For these trials, the processing line was run as slowly as possible (about 0.4 fpm) and appreciable cooling was observed in the forgings. Surface temperatures as low as 1300 F were recorded just before entry into the spray quench. These forgings probably did not soak through during the heating cycle. Cooling of the surface before quenching further increased the chances of inadequate heat treatment.

The conclusion from these trials was that the Drilco system as designed and presently operated (for drill collars, etc.) does not lend itself to heat treating thick walled gun tubes with large changes in cross section. With proper experimental development, however, the system could possibly be used for small tubes. One positive result was the excellent straightness of the forgings. Maximum deviation from a reference point along the centerline of the M185 was 0.1 inch, while for the M68 the maximum deviation was 0.2 inch.

Wall Thickness Effects

To determine tube sizes (wall thicknesses) that could be spray quenched in a facility presently in use, a contract was placed with National Forge to procure two large (9,000 lb) stepped forgings such as shown in Figure 4. One forging was quenched using outer surface sprays and a bore quench. The other was sprayed with water on the outer surface only, then given an extra (third) temper of ten hours at 1080 F. The extra temper was added by the vendor since impact energies for this forging were low after the second tempering cycle. Results of property measurements on the two tubes are given in Tables 4 and 5, respectively.

Simultaneous outer surface quenching and bore quenching resulted in better mechanical properties for equal tempering times. While impact energies for the two inch wall section were below specification limits, certified test reports from the vendor showed impact energies of 15 to 16 ft-lbs. In any case, extra tempering resulted in mechanical properties that met specification requirements even for a six inch wall tube quenched on the outside only. Since yield strengths for the outer surface and bore quenched forging were high, further tempering could be expected to yield mechanical properties that meet current specifications.

Solid Findings Reached

To determine if gun tube straightness would be affected by handling and transport of hot gun tube forgings to and from a spray quench tank, the mechanical properties of a gun steel metal (vanadium modified 4337) at high temperatures were investigated. Results (Table 6) indicated that the material has adequate stiffness for handling gun tube forgings at 1550 to 1600 F (the desired range for austenitization).

The results of this project confirm the following:

- Horizontal spray quenching is a satisfactory process for heat treatment of gun tube forgings.
- Tempering parameters strongly influence final mechanical properties if an adequate quench is obtained.
- Handling of most forgings at 1550 to 1600 F in a horizontal position should not significantly affect straightness if the forging is handled smoothly (without sudden jerks).
- Continuous heat treatment of gun tube forgings appears feasible in a properly designed system.

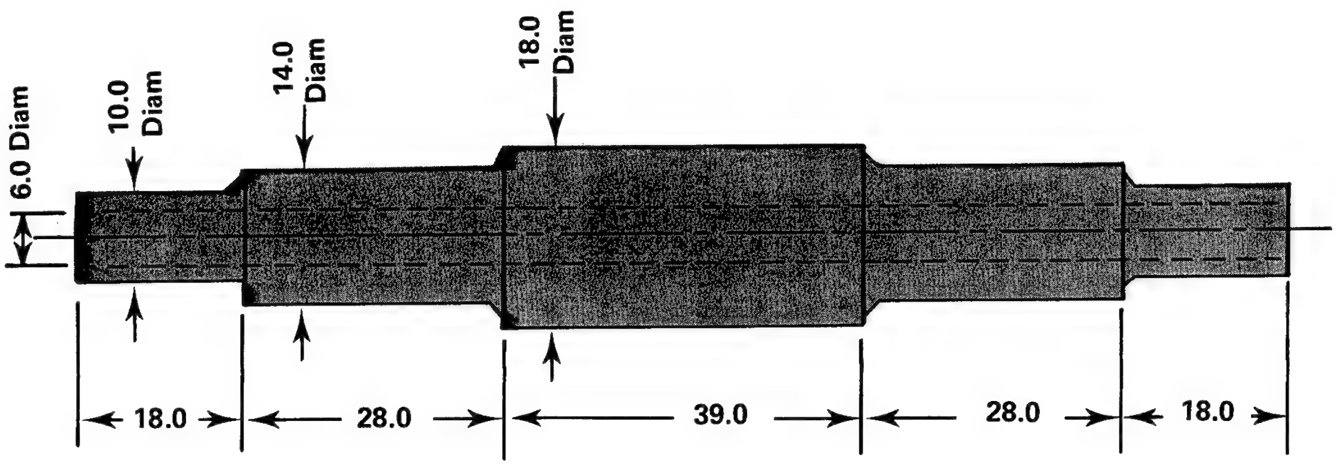


Figure 4

TRANSVERSE PROPERTIES						
Wall Thickness in.	Impact Strength Ft-lb (-40 F)	0.1% Yield Strength ksi	Ultimate Tensile Strength ksi	Elongation %	Reduction in Area %	K_{Ic} ksi$\sqrt{in.}$
2	14.5	172	187.5	12.6	36.2	91*
4	17.5	173	188	11.9	30.3	107*
6	17.5	179	193	13.1	35.7	110*
4	16.3	177	191	13.1	34.9	113**
2	14.6	172	186	12.8	34.2	93*
LONGITUDINAL PROPERTIES						
2	32.9	173	186	17.9	67.8	–
4	28.9	174	188	17.4	59.6	–
6	25.8	180*	194	16.2	51.1	–
4	30.5	175	190	17.9	58.6	–
2	33.5	173	186	18.4	59.5	–

*Single test.
**Average of two tests.

Table 4

TRANSVERSE PROPERTIES						
Wall Thickness in.	Impact Strength Ft-lb (-40 F)	0.1% Yield Strength ksi	Ultimate Tensile Strength ksi	Elongation %	Reduction in Area %	K_{Ic} ksi$\sqrt{in.}$
2	20.4	162	175	15.7	42.4	95*
4	22.1	167	179	15.2	43.5	103*
6	18.3	160	174	14.8	40.8	132**
4	20.6	169	182	13.6	39.8	112*
2	25.1	168	180	12.8	31.3	102*
LONGITUDINAL PROPERTIES						
2	40.5	[illegible]	[illegible]	[illegible]	54.5	–
4	[illegible]	160	175	17.4	57.0	–
6	26.0	161	176	17.8	57.4	–
4	35.5	167	180	17.4	57.8	–
2	40.7	163	175	[illegible]	59.0	–

*Single test.
**Average of two tests.

Table 5

Temperature, F	0.1% YS, ksi	0.02% YS, ksi	UTS, ksi	E, X10^6 psi
Room temperature	–	160.95	–	32.39
1000	136.4	122.24	155.6	18.31
1100	134.3	105.94	151.7	14.09
1200	124.2	71.30	135.4	11.97
1300	97.8	28.52	105.9	10.42
1500	21.2	10.59	22.9	8.54
1600	16.7	7.13	17.1	3.63
1700	7.34	4.28	8.35	–
1800	6.10	3.56	6.52	–
2000	3.05	1.24	3.79	–
2200	1.83	1.775	2.55	–

Table 6

References

(1) Gegg, C.C. "Practical Issues in Heat Treatment of Large Forgings", Journal of the Iron and Steel Institute, April 1967.

(2) Curtiss-Wright Corporation Report, "Feasibility Study on a Horizontal Quench Heat Treatment of a 175 mm Gun Tube", 15 September 1972.

(3) Crews, S.T., "Automated System Heat Treats Bars up to 60 Feet Long", Metal Progress, November 1972.

(4) Zimin, N.V., "The Effectiveness of Intense Spray Quenching", Metallovdenie; Termicheskaya Obrabotka Metallov No. 5, pp 23-26, May 1970.

(5) Dembowski, P.V., and Griffin, R.G., "The Effect of Austenitization Soak Times on Mechanical Properties", Report No. WTV-TR-75049, Benet Weapons Laboratories, Watervliet Arsenal, August 1975.

Production Line Automated

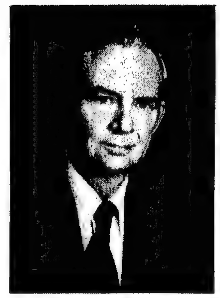
Streamlined LAP System For CCI Charges

Production of 155 mm and 8 inch Center Core Igniter (CCI) propelling charges with a new automated assembly system is forty times faster than the old manual system.

The Army significantly improved the accuracy and firing reliability of its heavy artillery by developing the 155 millimeter and 8 inch Center Core Igniter propelling charges that achieve 100 percent ignition. The next task was to develop an automated system which could meet mobilization rate production requirements for the subsequent CCI Load, Assemble, and Pack (LAP) operations.

In 1974, ARRADCOM initiated a program to develop an automated production line. The end product would

- Fit into existing buildings at the Indiana Army Assemble and Pack (INAAP) plant.
- Automatically dispense propelling charges to a weight accuracy of 0.06 percent.
- Fill charge bags uniformly and firmly.
- Produce 155 mm charges at 10 per minute or two increment 8 inch charges at two per minute with easily interchangeable tooling.
- Pack a snugly wrapped charge for safe transportation.



TAYLOR A. BIRCKHEAD is Principal Engineer at the MRC Corporation in Hunt Valley, Maryland. He has overall responsibility for the design, fabrication, and testing of the process improvement for 155 mm and 8 inch automated Load, Assembly, and Pack of Center Core Igniter propelling charges. Additionally, he proposed, developed, and designed other munitions and production upgrades, primarily in large caliber and underwater ordinance lines. He is also responsible for plastic products ranging from high speed sheeting systems to automatic thermoplastic container fabrications and the development, installations, and operational startup of related automatic or semiautomatic production lines. Before coming to MRC, he was part owner of Fiberglass Specialties, Inc., a plastics engineering firm. Prior to that, he served as Vice President of Engineering at the Belfort Instrument Co., where he designed and prepared meteorological, oceanographic, and photogrammetric instruments for the U. S. Weather Bureau, U. S. Army Map Service, and the GSA. Mr. Birckhead is the author of several patents in electronics and mechanical systems for plastics production. A graduate of LeHigh University, where he received a B.S. in Electrical Engineering, he has also taken courses at the U. S. Naval Mine Warfare School in Yorktown, Va. He is past president of the Baltimore Society of Plastics Engineers, past director of the Engineering Society of Baltimore, and is a member of the American Defense Preparedness Association (ADPA).

CLAUDE J. CARNALI has been a Project Engineer for ARRADCOM (formerly Picatinny Arsenal) in Dover, N.J., since 1962, where he has been developing automated production processing equipment for Load, Assemble, and Pack (LAP) operations for conventional ammunition. He has served on the Army's LAP Subcommittee for Modernization; he previously worked as an engineer for Western Electric, Ingersoll-Rand, and Mack Trucks, Inc. In addition to being a Registered Professional Engineer, Mr. Carnali is a member of the American Society of Mechanical Engineers (ASME), the Society of Manufacturing Engineers (SME), and the American Defense Preparedness Association (ADPA). He received a B.S. from the Indiana Institute of Technology and an M.S. from LeHigh University in Mechanical Engineering.

NOTE: This manufacturing technology project that was conducted by MRC Corporation, Hunt Valley, Maryland, was funded by the U.S. Army Armament R&D Command under the overall direction of the U.S. Army Office of Manufacturing Technology, DARCOM. The ARRADCOM Project Engineer is Mr. Claude J. Carnali (201)328-4162.

Feasibility Study Initiated

MRC Corporation of Baltimore was awarded the multiphase development contract. Phase I was the feasibility study, and initially addressed the following questions:

(1) Could the bags be filled compactly at a uniform rate?

(2) Could the triple base, large grain propellant be handled in quantities required?

(3) How could the rates of production be met within the confines of the building specified?

In response to the first two questions, compaction tests using the various grain sizes were conducted in a cylinder approximately three feet high. Grain sizes for the CCI propellant charges ranged from 1.5 to 5 g. The larger pellet increments were used for the 26 lb XM 203 (155mm) and the 38 lb XM 188 (8 inch) charges and weighed 3.09 g and 4.87 g, respectively. The effect of vibration on loading density was determined (Figure 1), and it was discovered that the flow behavior of the larger pellets was dissimilar to that of the smaller pellets. In order to attain rapid bulk compaction, it became necessary to couple a graduated vibration amplitude with a controlled fill rate. One bonus of this controlled ratio is that it offers approximately 8 lb/cu ft **greater** loading density in less time than in the normally operated production line. A commercial iris valve to control propellant flow made it possible to develop a volume receiver batching system. This system can replace batteries of parallel scales otherwise needed for measuring 26 lb lots of propellant material at the required 0.06 accuracy. This accuracy figure refers to approximately 11,800 g to ±7 g tolerance when one pellet weighs 3.5 g.

In order to evaluate the usability of the specified building, four alternative LAP processes were developed. These concepts are illustrated in Figure 2, representing an increasing amount of automated vs. manual production. It was recognized early that, because of the complexity of several operations, full automation could not be attempted at the time of the project. Therefore, a combination of automated and manual operation using a modular approach was selected for development.

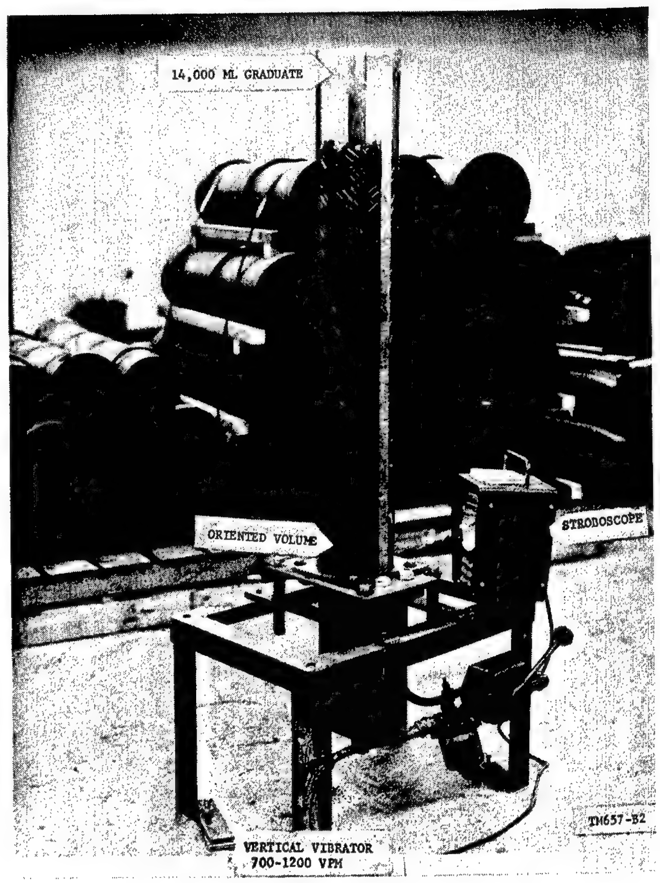


Figure 1

LAP Processes Analyzed

The next step of the feasibility study included analysis of LAP equipment and processes. The building includes three load rooms—two to produce five increments per minute and one as a standby or production alternate for an additional 25 percent greater output.

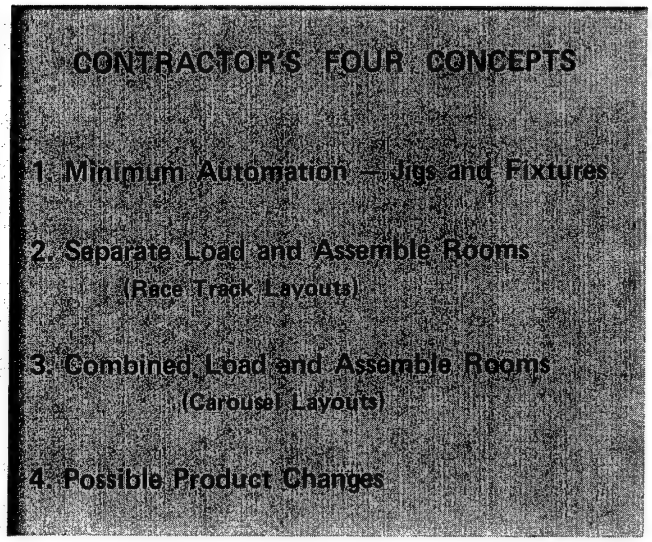


Figure 2

Increments leaving the load room are directed to a hallway buffer for storage until needed in the assembly room. Rejects bypass the buffer for a cutdown operation. Assembly rooms are relatively small—10 ft 4 in. wide by 20 ft long. However, only two assembly rooms are needed, since the equipment is less complex and has an additional 25 percent standby.

Mandrels (metal bars) are left in the increments to maintain firmness of load and trueness of center pocket during transportation. They are taken back to the load room after they are extracted from the center core igniter tube. The charges move on to one of three hallway buffers. The third buffer receives jacketed charges from a manually operated jacketing room. Jacketing, only a possible design item during the feasibility study, completes the charges. The jacketed charges are ready for packout from buffer storage.

The packout process is based on the concept of an old fashioned cigarette rolling machine. Charges are wrapped in a corrugated sheet that is automatically dispensed at an adjustable, premeasured length. The system provides long filler strips and ultimately stuffs the materials into canisters.

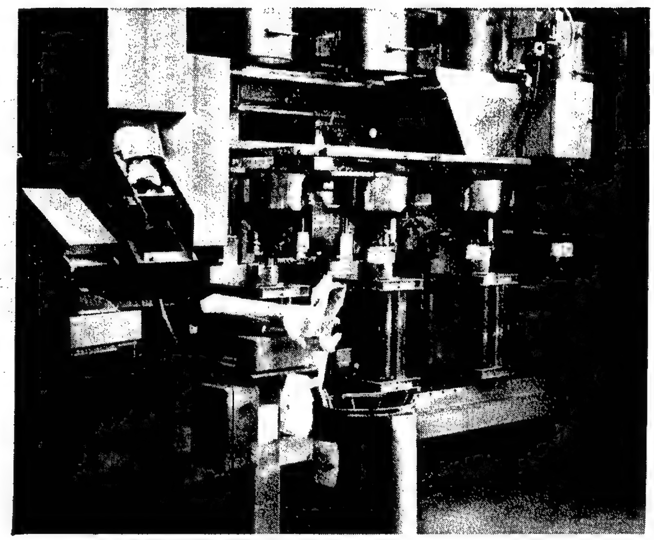


Figure 3

Load Room Equipment Developed

Phase II of the project called for the development, design, and fabrication of the load room equipment. Several major improvements resulted from this program, including the safe stacking of propellant above the material's "critical height", an all air logic control system in hazardous areas, and intrinsically safe scale bases. In developing the latter, Allegheny Ballistics Laboratories (ABL) used zener barriers (a grounding fuse device) in a "foolproof" mechanical-electrical system. Computerization created other developments including the Program Logic Control (PLC) system for basic equipment direction, scale reading analysis of each cycle, and taped program interchangeability for different charge loadings. Readouts with central building and plant control capability data and with production figures will eventually be developed.

A hazards analysis conducted by the ABL confirmed the safety of the perforated sheet metal shrouds used to

support bags during loading. The study also produced data indicating that a fire could be extinguished or subdued by dousing it with water.

In July and August of 1976, the load module was successfully demonstrated. Figure 3 illustrates the front view ready for simulated operation. The control cabinet with PLC and air-electric interfaces is on the right, as is a conveyor which represents the second floor propellant supply and hopper system. Figure 5 depicts the rear view of the module and shows incoming pellets feeding the volume receiver, which works on the basis of inches of pellet column length instead of number of grains. The module initially will release up to 209 g of M30A1 propellant for the first weighing and an additional trim amount after the second. After the accept/reject checkweigh on the third scale, the buckets dump their load, moving the pellets into the bag filling operation.

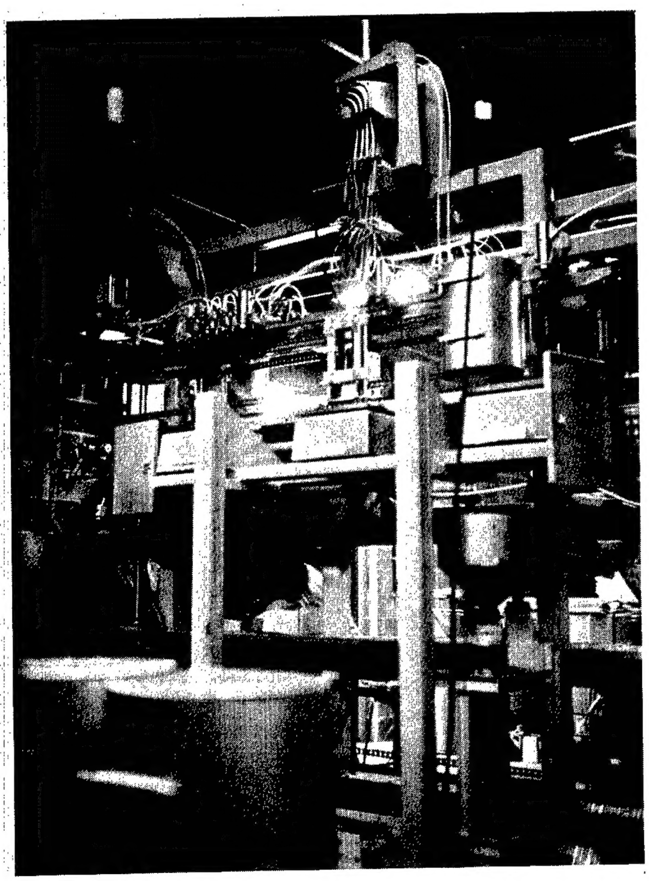


Figure 4

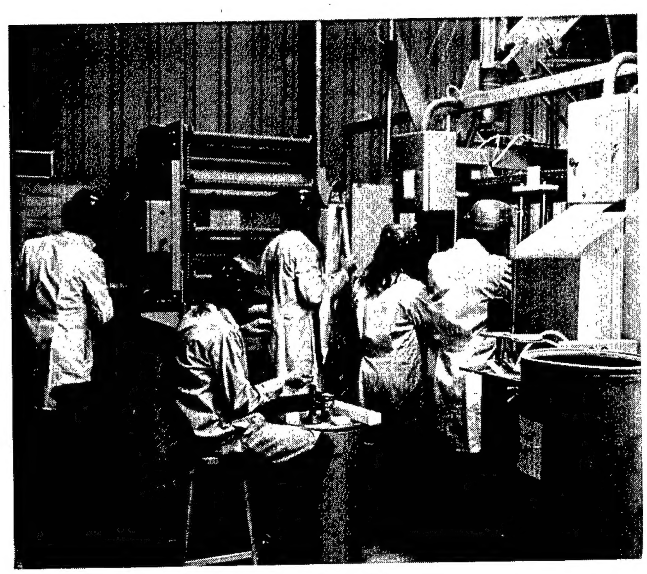


Figure 5

AVRADCOM Begins

Army's Tech-Mod Equivalent

A new effort has begun at the U.S. Army Aviation Research and Development Command in St. Louis, which is one of the first Army commands to initiate the new Manufacturing Productivity Improvement Program (MPIP) similar to the Air Force's Tech-Mod Program. These program thrusts are designed to reduce the cost of military weapons systems through incentives to contractors to use the most modern technologies available in manufacturing military items.

Mr. Gerald A. Gorline has been designated Program Manager for this new AVRADCOM system of procurement and implementation of technologies that have been developed by the manufacturing programs of the past 18 years.

Assemble Module Fabricated

Phase III covered the development, design, and fabrication of the currently operating assemble module (Figure 5). Assembly module operations include the CCI insertion, tack sewing of the igniter base pad, and addition of the flash reducer to the opposite end. An assembled charge is tied to longitudinal straps and sent on its way via a conveyor belt.

A typical curve (Figure 6) was developed in testing and demonstrating the load and assemble modules. Performance of the volume dispenser per Scale #1 weighings, first pellet dispense per Scale #2, and trim dispense per Scale #3 are plotted on the curve to a magnified weight scale.

Packout for Charges Designed

Phase IV includes the development, design, and fabrication of the packout for the charges. Included in the completed development is an operating mockup of the wrapping machine. A hazards analysis similar to that conducted on the load and assemble modules was performed. Also, each of the three prototype equipment sets has its own PLC. In sum, each of the three components of the loading system—L, A, and P— is a self contained unit while furnishing production data to a central system. The system can also be operated by a single control center.

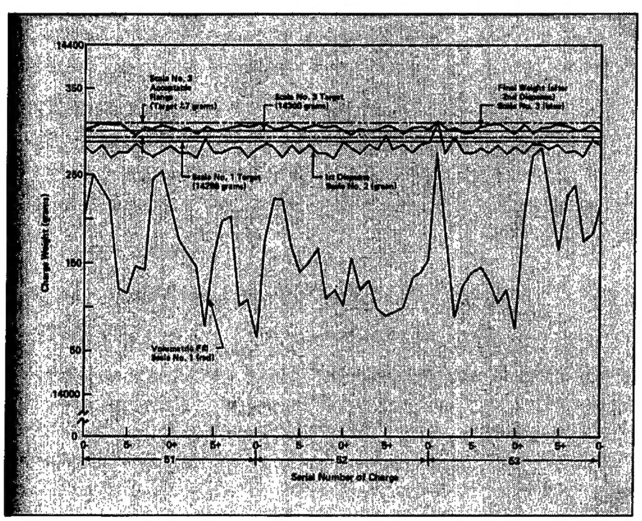


Figure 6

Goals Achieved

The first four phases of the project have accomplished the goals set forth at the beginning of the article:

- Although the prototype equipment could be accommodated in existing buildings at INAAP, conditions were crowded. The equipment was consequently redirected to Crane Army Ammunition Activity, which has more space. Second generation equipment will be installed at INAAP in a new, larger facility and will be redesigned to take advantage of all available space.
- The load module will produce bags of propellant to an automatic weight accuracy of 0.06 percent.
- Bags can be filled uniformly and firmly.
- Additional debugging of the load and assemble modules will produce the desired rates of production and required tool interchangeability.

Automated LAP Prototype Near Completion

Phase V of the program included construction of the buffers, design, and implementation of specifications for hallway conveyors and interfacing and conduction of additional hazards analyses. After the necessary simulated tests have been run at the Crane Army Ammunition Activity facility, Phase V will be completed and automated LAP for CCI propelling charges will become a reality.

MPIP Effort

How It works

The mechanics of the program in outline form are:

- Technical analysis is made of a contractor's complete manufacturing and business operation.
  —Identify cost drivers (low productivity)
  —Identify mantech projects
  —Identify facilities to improve producibility and reduce cost
  —Identify investment strategy (how industry and government will share)
- Funding—industry and government co-fund the effort by contract. Similar to the Air Force Tech-Mod effort on the F-16, for which the investment ratio (industry/government) was approximately 5:1.
- Return on Investment (ROI)—industry benefits by sharing in the savings and improving its manufacturing facilities. Government benefits from the reduction in cost of weapons systems.

Figure 1 shows this procedure graphically.

Whose Involved?

Contractors who will be asked to participate in this new productivity improvement program are under consideration. Other Army commands implementing the Tech-Mod program are the U.S. Army Missile Command at Redstone Arsenal, Alabama, and the U.S. Army Troop Support and Aviation Readiness Command in St. Louis, Missouri. Procedures for these programs are not completely formulated yet, but will be developed and changed or modified as experience is gained during the MPIP activity. However, Army agencies plan to model their procedures after those being established by the Air Force in its current Tech-Mod contracting. The Army's methods of awarding contracts for military items will be modified to favor firms that use the most advanced manufacturing technology available. Army requests for proposals will contain provisions requiring bidders to adopt the most innovative and efficient approaches available—technologies that will improve their productivity and cut manufacturing costs.

Fundamental Shift A Result

Selection of a prime contractor will take into consideration the proposed new manufacturing technologies, how they will increase productivity, and the contractor's willingness to invest in capital equipment. Mantech money will help the contractor implement both plant and equipment modernization for use of this technology. Since the Army's productivity improvement program is just getting started, clarification will be made available as experience is gained.

The new DARCOM push for implementation of newly developed manufacturing technologies and the reaping of benefits from these investments reflects a fundamental shift in relationship between the military procurement agencies and the industrial suppliers. Most of those involved with Army mantech programs feel that the impact of this new approach will be felt widely in the nonmilitary commercial sector as well. One of the basic objectives is to stimulate increased capital investment for productivity within the Army's suppliers. To do so, contracting on a multiyear basis is expected to favorably influence these objectives, which by nature require a long range perspective.

Multiyear Contracting Used

The multiyear contract used by the Air Force in their tech-mod effort and its use by others will have an impact, also, on the short term perspective toward return on investment currently the preoccupation of today's managers in industry. Longer term planning in capital investment now will become possible with the help provided by multi-

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year contracts and military funding to implement new technologies. Another factor that will have a widely felt impact on the nonmilitary commercial sector is the requirement being written into the current Air Force tech-mod programs that participating firms cooperate and share new technology and its means of implementation.

Funding Preceding Award

Most of the money used so far in the Air Force's efforts in this area have been targeted toward developing practical means for using known manufacturing technologies. The major portion of the joint capital venture between military and industry has been industry's capital investment—a 4:1 ratio in the case of the F-16 program. The Air Force reports that long range planning will be more practical as a result of multiyear contracts, and tech-mod money will become available during technology development prior to award of a contract to a prime bidder. More than one potential bidder may qualify for developmental funding far in advance of contract award as the means for implementing known but previously untried technologies are worked out.

A common sharing of systems of implementation that are developed will mean diffusion into all sectors of our production economy, both military and civilian, with a beneficial impact on our national productivity that will have far reaching effects.

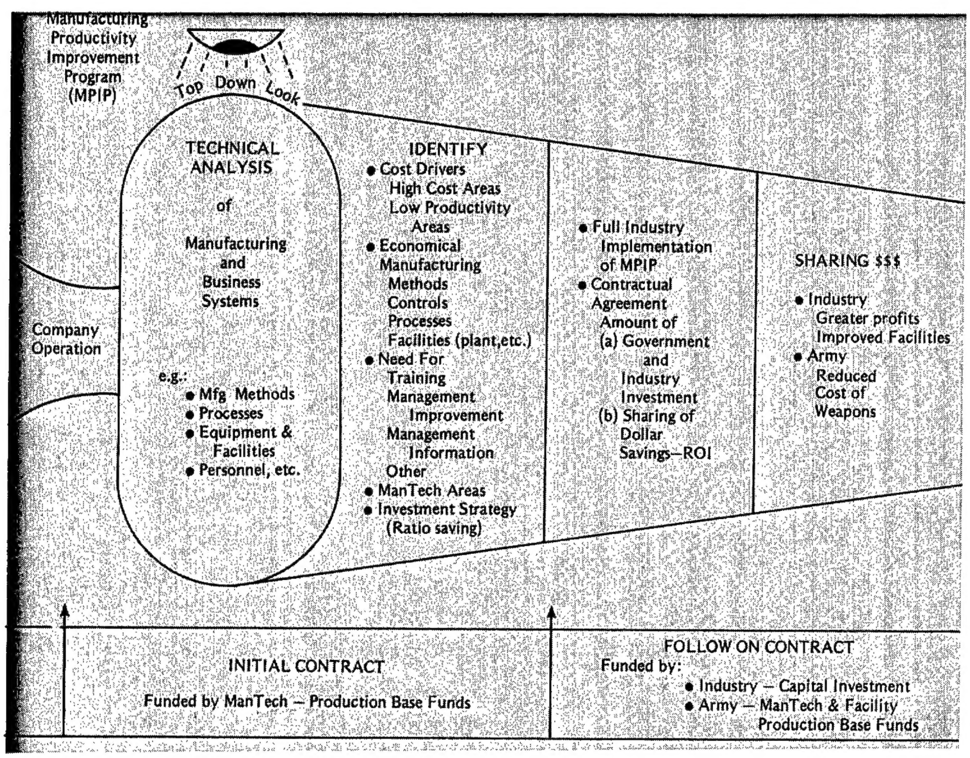

Figure 1